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CHAPTER 3: GEOMORPHOLOGY

BACKGROUND

The contact geology of the San Juan River Basin ranges in age from Precambrian to Holocene. The lithology at the headwaters of the San Juan Mountains is primarily crystalline, igneous, and metamorphic. Sedimentary sandstone, siltstone, and shale of both marine and continental origin underlie the lower river reaches found in the study area (Thompson 1982). Much of the floodplain and adjacent terraces within the study area are overlain by quaternary sand, gravel, and cobble deposits. These alluvial deposits were derived from the resistant igneous and metamorphic rock of the river headwaters, thereby providing a rich source of durable cobble throughout the study area (Miser 1924, O'Sullivan et al. 1957). The active sediment load (bedload and suspended sediment) in the system mainly originates from the highly erodible sedimentary rock and aolian sand deposits.

The geomorphology of the system is heavily influenced by the large sediment load resulting from high intensity storm runoff on the un-protected, highly erodible watershed, primarily south and west of Navajo dam.. The first major sediment source in the study area, Canyon Largo, occurs 19 mi downstream of Navajo Dam. The frequency of similar ephemeral tributaries with high sediment loads increases downstream, thereby disproportionately increasing total sediment load relative to flow in the main river. The result is an extremely high sediment load in the lower reaches of the river. This large, active sediment load in the lower river plays an important role in the formation and maintenance of instream habitat.

Both flow and sediment load have varied over time, due both to natural climatic cycles and man's influence. These changes have altered the sediment transport regime in the system with alternating periods of deposition and scour. This history and its influence on channel form have been examined and are reported here.

The geomorphology varies considerably in the study area. While the gradient does not vary greatly, it is generally steeper in the upper portion of the river and flatter in the downstream portion, gradually changing over the full reach (Figure 3.1). The lower 110 km and upper 15 km are canyon bound, while the middle section flows through valleys of varying width. Some cobble exists in the substrate throughout the study reach, with the exception of the lower 16 miles, but the percent composition relative to sand decreases with distance downstream. Through the valley reach, the system is primarily characterized as anastomosed or multi-channeled, with heavy to moderate riparian vegetation, moderate slope, and low channel sinuosity. Human-induced impacts include enhancement of riparian vegetation due to irrigation return flow, elevated groundwater adjacent to irrigated lands, and the presence of five diversion dams between RM 140 and RM 180 which affect bed elevation. The details of the variation in geomorphological characterization are provided as a result of studies described in this Chapter.

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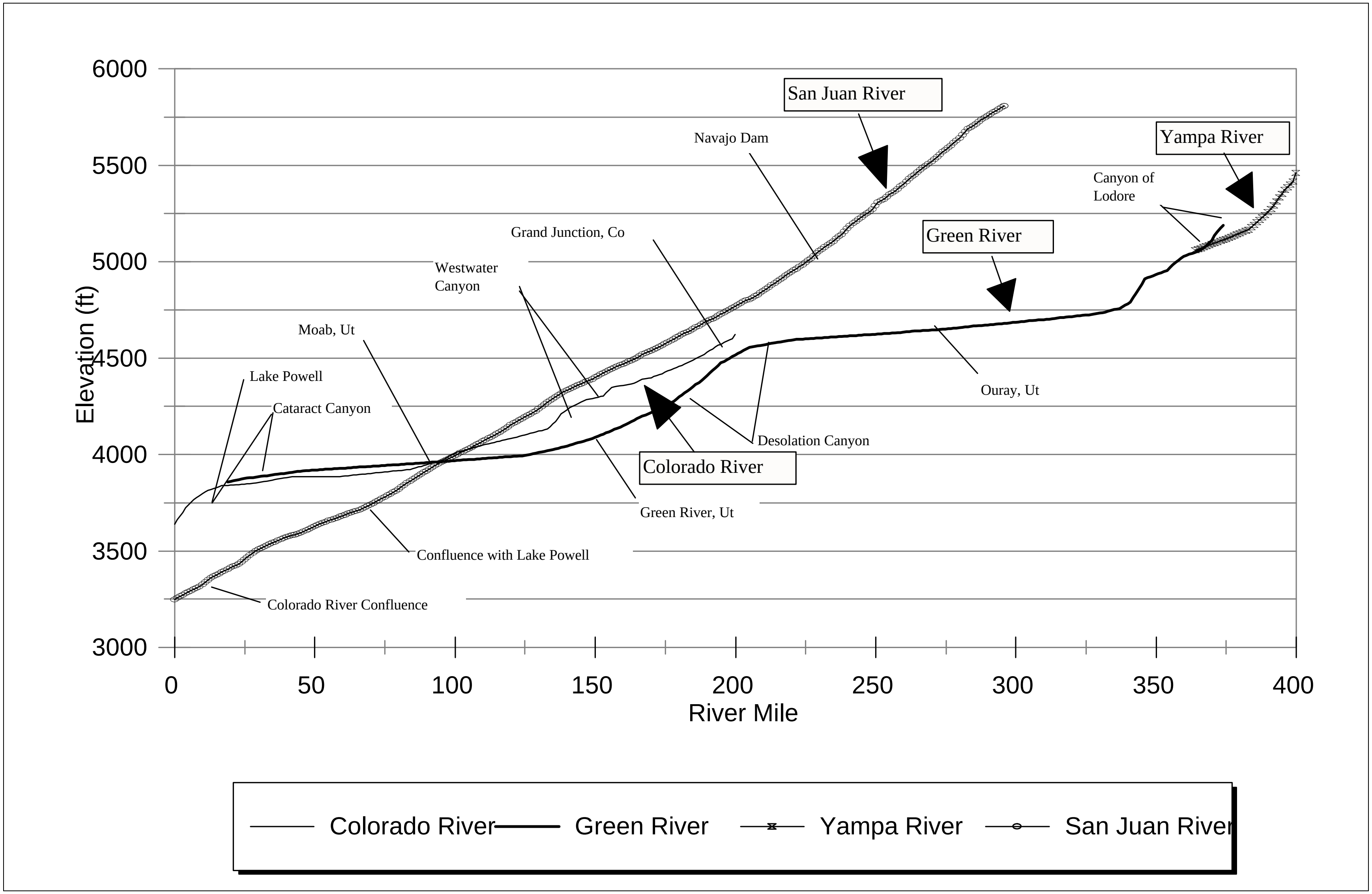

Figure 3.1. San Juan River Gradient

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OBJECTIVES

Historical Analysis of Fluvial Morphology

It has been hypothesized by those that have studied the endangered fish in the San Juan River, that a major contributor to the decline of the species has been the loss of the natural flow regime and its effect upon habitat for the endangered fish (SJRIP, 1991). An understanding of the nature of the fluvial morphology of the river prior to regulation by Navajo Dam and the change associated with regulation is helpful in testing this hypothesis. The objective of the historical analysis of fluvial morphology of the San Juan River is to determine changes that have occurred over time as a result of natural forces and man's influence in the basin, including regulation by Navajo Dam.

Geomorphological Characterization

The entire river from Navajo Dam to Lake Powell does not likely respond the same to flows. To aid in the understanding of response, geomorphologically distinct reaches were defined to refine the characterization of the river.

Channel Geometry Analysis

A key objective of the seven year research study was to determine the response of the San Juan River Channel morphology to hydrographic conditions resulting from the range of research releases from Navajo Dam. (SJRIP, 1995 The long range plan). One of the responses deals with the change in the channel geometry as a result of the various test flows. The channel geometry studies were completed to determine the general response of the channel in terms of depth, width and complexity, to the new flow regime.

Cobble Substrate Characterization

The production of clean cobble for spawning areas is dependent upon entrainment of cobble during high flow periods just prior to spawning and deposition of the cobble under conditions that allow it to be placed relatively cleanly, without significant sand and fines to fill the interstitial spaces. An important part of determining flow requirements for the endangered fish species is an understanding of the conditions required to entrain cobble of the size necessary for proper spawning. To fully understand the process, the size of the substrate to be moved and the hydraulic conditions required to move it must be determined and compared to the conditions that exist at critical locations in the river.

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Suspended Sediment Analysis

Changes in the hydrology of a system change the sediment transport regime. Sediment concentration measurements during runoff were made to allow comparison of the new sediment transport conditions during runoff to the change in cross-section measurement. Secondarily, the sediment concentration data were compared to historic data for validation.

METHODS

Historic Analysis of Fluvial Morphology

Historical aerial photography has been obtained from the 1930's, 1950's, 1960's and 1980's. No single flight was available for any one year, so aerial photography from multiple years in close proximity were used to obtain full coverage for a given time period. The flight years and river coverage are provided in Table 3.1 for each of the four time periods. The analysis was completed for geomorphological reaches three through eight. Reaches one and two are canyon bound, were not expected to exhibit changes in channel morphology and were not included in the analysis. Of the six reaches analyzed, four (reaches three through six) are within the critical habitat for the endangered fish.

This aerial photography was optically registered to 4:1 enlargements of USGS quad sheet base maps. The bankfull river channel was hand plotted in the rectification process and then digitized for analysis. The data were processed in ArcCad, a geographic information system extension for AutoCad that produces ArcInfo coverages. Cross-tabulations of island area, island count and channel area by river mile were produced for analysis.

Water surface area could not be compared due to the range of flowrates at which the photography was taken. Analysis was limited to a comparison of the bankfull channel area, island area and island count as a measure of change in channel capacity and complexity. Unfortunately, channel complexity during low flow conditions could not be compared since much of the photography was not obtained during low flow conditions.

Geomorphological Characterization

Observations over the past three years of field work and data review indicate variability in the geomorphological characteristics of the San Juan River between Navajo Dam and Lake Powell. It was theorized that channel morphology and aquatic habitat may respond to hydrologic conditions differently in different sections of the river. Therefore, defining reaches that are geomorphologically distinct could aid in analysis of the system to better understand the response to the hydrograph.

Forty-nine individual data sets in eight categories were developed. These data sets were used to define distinctly different river reaches.

Table 3.1. Aerial photography coverage by river mile used in the historical analysis for the periods 1935-1937, 1950-1952, 1959-1962, and 1986-1988.

1935-1937 Series*			1950-1952 Series		
Photo Date	RM	Flow Rate at closest gage (cfs)	Photo Date	RM	Flow Rate at closest gage (cfs)
1935	66-77	N/A	02-Oct-52	66	1,000
1934	77-97	N/A	04-Nov-52	67-69	461
1935	94-224	N/A	01-Oct-52	70-72	1,040
			14-Oct-52	73-75	579
			26-Jun-50	76-96	2,200
			28-May-55	97-98	4,780
			04-Sep-52	99-102	816
			07-Oct-52	103-106	714
			11-Nov-52	107-111	768
			04-Sep-52	112-118	816
			26-Jun-50	119-120	534
			14-Sep-52	121-125	607
			22-Aug-52	126-132	607
			06-Oct-52	133-134	930
			15-Aug-52	135-141	607
			28-Nov-50	144-158	828
			28-Nov-50	159-176	350
			12-Nov-50	177-190	224
			28-Nov-50	191-201	216
			12-Nov-50	202-223	324
			28-Nov-50	224	216

1959-1962 Series			1986-1988 Series		
Photo Date	RM	Flow Rate at closest gage (cfs)	Photo Date	RM	Flow Rate at closest gage (cfs)
28-Aug-59	66-75	1,270	28-May-88	66-99	1,700
06-Sep-61	76-93	697	28-May-88	100-129	1,680
06-Sep-59	94-99	238	28-May-88	121-150	1,610
28-Aug-59	100-106	1,270	14-Jun-86	151-158	5,180
31-Aug-59	107-113	730	14-Jun-86	159-169	5,770
06-Sep-59	114-116	238	18-Jun-86	171-180	5,630
14-Aug-62	117-158	395	18-Jun-86	181-193	1,750
14-Aug-62	159-180	526	17-Jun-86	194-202	1,510
14-Aug-62	181	597	18-Jun-86	203-214	1,750
17-Aug-62	182-199	345	29-Jul-86	215-224	3,230
24-Aug-62	200-224	315			

* Dates of 1934-1935 photography not available to determine flow rate

River Valley Geometry

Valley width was determined utilizing generalized geology maps of the basin prepared by USGS 1965, USGS 7.5 minute quadrangle maps and 1986-1988 aerial photography. The boundary of the alluvial San Juan River valley was mapped on the USGS quadrangle base utilizing the generalized geology maps as the first level of interpretation with elevation break and aerial photography interpretation as the means of refinement. The boundary definition used as a refinement to the small scale geology maps was the existence of bedrock at the edge of the valley defined by two adjacent 20 ft contours with verification of this boundary with aerial photography. The valley boundaries were digitized into the GIS system and the mean width per river mile computed.

Below RM 68, the valley width was taken as the width of the water surface at the highest flowrate for which habitat mapping was completed (approximately 257 m^3/sec (9,090 cfs)). For this canyon bound reach, this is a reasonable approximation of valley width and allows extension of the data set for the full length of the study area.

Channel Contact Geology

In November 1994 river channel contact geology was mapped from the confluence of the Animas and San Juan rivers (RM 181) to the beginning of the canyon reach at the Chinle Creek confluence (RM 68). The mapping was not comprehensive, but consisted of mapping the location and extent of cutbanks along the main channel and then identifying the material in these cutbanks. Cutbanks were defined as vertical or near vertical banks exhibiting erosional characteristics. Layered material was noted with each layer being characterized as one of the classifications shown in Table 3.2. In addition, any channel contact with bedrock or talus slopes was also noted. Mapping cutbanks not only allowed an assessment of the longitudinal distribution of cobble, gravel, sand and bedrock contact, but an assessment of channel stability as well.

Contact areas were mapped from a boat by visually noting the beginning and ending of cutbanks or bedrock contact and marking these locations and the classifications on prints of aerial videography flown 8 November 1994. This information was transferred to scale rectified base maps by projection and the lengths measured for each segment. A database of the length of each contact type by river mile was constructed for data analysis.

Riparian Vegetation

Riparian vegetation was identified and mapped from the confluence of the Animas and San Juan Rivers (RM 181) to the confluence of Chinle Creek (RM 68) during November 1994. The base map used consisted of prints of the November 1994 videography at a nominal scale of 1:3000. Vegetation complexes were categorized as shown in Table 3.3. Three density ranges of each vegetation type were categorized. Vegetation complexes were delineated on the aerial videography prints based on interpretation of the videography and ground inspection. Complexes were mapped that could be identified from the river side as the mappers floated past, extending the range away from the river by

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Table 3.2. Stream channel contact geology descriptions used in mapping.

Code	Description	Code	Description
S	Sand, 2mm and smaller	RR	Riprap stabilized
SGr	Sandy Gravel, > 25% gravel	BR	Bedrock stabilized
SCb	Sandy Cobble, > 25% cobble	BR + SS	sandstone
Gr	Gravel , <3" diameter	BR + SiS	siltstone
GrS	Gravelly Sand, < 25% gravel	BR + Sh	shale
Cb	Cobble > 3" diameter	TA	Talus stabilized
GrCb	Gravelly Cobble, < 25% gravel		

Table 3.3. Vegetation types and codes used in mapping riparian vegetation.

	Percent Cover		
Vegetation Type	1-25%	26-75%	76-100%
	Code		
Cottonwood Canopy	1	2	3
Russian olive canopy	4	5	6
Tamarisk canopy	7	8	9
Willow canopy	10	11	12
other tree species	13	14	15
upland herbaceous understory	21	22	23
upland shrub understory	24	25	26
wetland herbaceous understory	27	28	29

common visual signature on the video prints. This method limited the extent of mapping possible to something less than the full flood plain. However, the width of coverage was sufficient to allow assessment of the riparian vegetation that could potentially influence channel pattern and riverine habitat.

The delineated vegetation polygons were optically projected onto the same base map set used for habitat registration and then digitized for analysis in the GIS system. Since the full extent of riparian vegetation was not mapped, a method of standardization was needed to allow analysis of

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longitudinal distribution. A 30 meter wide band on either side of the main channel was selected as the standard. In braided locations one channel was selected that represented the main channel at about 28 m^3/sec (1,000 cfs). In areas of small islands, the outer channel banks became the boundaries and the vegetation on the islands excluded from analysis, leaving just the 30 meter band of vegetation on either side of the channel.

To assess distribution of plant species, the percent density (midpoint of the mapping category) was multiplied by the area of all polygons that contain that species or type and extracted from the database by river mile. Therefore the analysis reflects both extent and density in a lumped term. However, the area and density are preserved separately in the database if needed.

Channel Gradient

Channel gradient was determined from USGS 7.5 minute quadrangle maps. It was assumed that the general channel gradient was constant between contour intervals. Channel slope by river mile was computed by linear interpolation between contour intervals. While channel slope calculated in this manner is not accurate locally, it reflects the average slope of longer reaches of river with acceptable accuracy. For the purpose of defining the average slope of a selected river reach, the method is appropriate.

Channel Pattern

Channel pattern was assessed by measurement of two parameters: sinuosity and braiding. Sinuosity is defined as the length of the thalweg of the river divided by the length of the valley trend. Valley trend was determined from USGS 7.5 minute quadrangle maps on which the valley boundaries had been drawn. The valley trend line was drawn centered in the river channel but aligned with the general trend of the valley. This line was digitized and the length of the line per river mile determined. In computing sinuosity a moving 3-river mile length of channel from the 1992 digitization was divided by a moving 3-river mile length of valley trend. In the canyon, the valley trend was taken as the same length as the channel, since the river cannot meander inside the valley constraints. In the lower 14 miles where the thalweg is meandering in the sand bottom, the sinuosity is under-estimated, but it is still very close to 1.0 because of the narrow confines of the meander.

Channel complexity was assessed by measurement of island area by river mile. In as much as island area and channel complexity vary with flowrate, island area was assessed at each of the flowrates for which habitat was mapped. The average values at high (June 1993, 1994), intermediate (July 1993) and low flows (November 1992, October 1993, and August 1994) were computed and these averaged data sets used in analysis.

Tributary Influence

For the full length of the river from Navajo Dam to Lake Powell, the location and type of tributaries was noted. All perennial tributaries were identified and the river mile and side of river entry noted in the database. In addition, major ephemeral tributaries, those contributing substantial amounts of sediment to the system, were identified in the same manner. This data set was used in channel reach definition and will be used in assessing localized impact on geomorphology and habitat if such relationships exist.

Man's Influence

Nine categories of man's influence were mapped: adjacent irrigation, bridges, diversion dams, oil wells in the flood plain, pipeline crossings, borrow pits, ponds, roads and sewage treatment facilities. To be included, the facility had to be adjacent to the river channel or in the flood plain. For roads, they had to exhibit some potential control on the river channel, usually demonstrating the existence of a levee along the channel. These categorical variables were entered by river mile as existing or not existing.

Aquatic Habitat

Six categories of aquatic habitat data were used in the analysis from six mapping trips. The categories used were: total water surface, low velocity (backwater, embayment, eddy & pool), riffles/chutes, sand types (sand shoals, sand bars), cobble types (cobble shoals, cobble bars) and island area. The categories were averaged for low, intermediate and high flow conditions as described under Channel Pattern. Island area was used as part of the channel pattern description and the sand and cobble types were used in conjunction with the channel geology information.

Identify River Reach

All of the above described data sets were used to identify distinct river reaches. Table 3.4 summarizes the data sets used and the coverage of each data set. The procedure used to identify distinct reaches consisted of three steps:

1. Identify test reaches based on general survey information.

   The river was divided into test reaches based on general observations derived from the surveys. These test reaches appeared to be distinctly different, but the boundaries between reaches were not precisely known and the degree of difference was not quantified. The test reaches selected are described in Table 3.5.

2. Select a model to find differences between reaches.

   After trying several different statistical models, a multi-variate model called linear discriminant analysis was chosen. This model was originally developed by Fisher (1936) to allocate individuals to one of several populations on the basis of a measurement of a multidimensional random variable on the individual river mile in this case.

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Table 3.4. Data sets used in channel reach definition analysis.

HABITAT - m^2/mi	Coverage - River Miles	
Total Water Surface Low Velocity Types Riffles/Chutes Cobble Type Island 3 mi average	High Flow Intermediate Flow Low Flow	0 - 224 0 - 158 0 - 224
RIPARIAN VEGETATION - m^2/mi	68 - 180	
Cottonwood Russian Olive Tamarisk Willow Upland Herbaceous Upland Shrub Wetland Herbaceous		
CHANNEL - 3 mile average	0 - 224	
Valley Width - m Channel Slope - ft/ft Sinuosity		
STREAM CHANNEL	68 - 180	
Bedrock - m/mi Total Cutback Contains Sand Contains Gravel Contains Cobble Sand Only Gravel Only Cobble Only		
CATEGORICAL VARIABLES	0 - 224	
Adjacent Irrigated Area - % Major Tributary - Ephemeral Major Tributary - Perennial Bridge Diversion Oil Well Pipe Crossing Borrow Pit Pond Road Sewage Treatment		

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Table 3.5. Location descriptions of general reaches in San Juan River having different characteristics.

Reach	Description
1	Waterfall/Lake Powell influenced reach
2	Canyon bounded reach up to Chinle Wash
3	Chinle Wash to Aneth
4	Aneth to Mixer
5	Mixer to Hogback diversion
6	Hogback diversion to Animas confluence
7	Animas confluence to Blanco
8	Blanco to Navajo Dam

Discriminant analysis treats the measured variables as random variables, each set arising from two or more populations. Linear combinations of the measured variables are constructed which exhibit properties of maximum variance and no covariance. These linear combinations, canonical variates, form a new set of linearly independent variables which maximize the "distances" between each population. During the course of the analysis, statistically insignificant variables can be eliminated. Finally the question is - given the chosen set of variables, are the population "distances" sufficiently large enough to distinguish between populations? If so, then assign unknown individuals with a known degree of uncertainty to a population. We were not interested in this last step. Instead we wanted to use the statistical information gathered during the process to determine which variables are the most important in defining the reaches, if the division of the San Juan River into eight reaches was justified and to define the division points.

3. Use the model to find reaches and validate results.

The analysis was first restricted to variables only measured along the entire river. From Table 3.4 these variables are those belonging to conditions of high and low flow, channel parameters and the categorical variables. Later as a cross-validation on the reach designations for 3 through 6, we also added the vegetation/channel contact variables and reran the analysis on the restricted set of reaches.

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Channel Geometry Analysis

Four separate studies were completed. The first set of studies examined the response of channel geometery to flow at newly established locations throughout the lower 6 reaches of the river comprising the critical habitat of the endangered fish. The second analyzed long term change in channel geometry at USGS gage locations, examining scour and deposition in response to flow. The third examined the impact of change in channel geometry on channel complexity. The fourth analyzed the change in channel capacity as a result of changes in channel geometry during the study period.

Cross-Section Measurement in Representative River Transects

In 1992, eleven river transects, indicated as "RT" cross-sections, were established with permanent monuments. The sites were selected to be representative of overall channel capacity change. The eleven transects were placed at the end of long runs at a control section immediately upstream of a channel split. The locations are shown in Figure 1.1.

At each transect a benchmark was established by embedding a brass monument in concrete. On the opposite river bank, a tree or other stable landmark was used to both mark the cross section and attach a cable that was used for stationing across the river during surveying. The entire cross section of the river was surveyed. Channel bottom elevations were measured every five to ten feet, depending on the width of the river. All elevations were tied to the newly established benchmark. The benchmark at each transect was assigned an arbitrary elevation of 100 feet. Subsequent surveys of the same cross section were tied to the same bench mark allowing accurate comparison of changes in bed elevation with time. Surveys were completed pre- and post-runoff, typically in February or March and again in August.

In addition to surveying each transect, the proportion and type of primary substrate were estimated. The major classifications were cobble, gravel and "fines".

All measured cross sections and subsequent calculations of scour and deposition are maintained in AutoCAD. In addition to cross section information, substrate conditions are also stored in AutoCAD.

Fifteen additional transects were established in 1993 to more closely monitor channel change in the vicinity of 1993 suspected spawning sites and in areas that exhibited significant change in 1993. Eight are located in the "mixer" reach (RM 129 - 134), five in the reach between RM 83 and RM 88 referred to as the "debris field" and two in the reach between RM 0 and RM 14 (Clay Hills). Those in the mixer cover locations of suspected spawning in 1993 and 1994, locations of significant cobble movement or locations to provide information for hydraulic modeling. The reach between RM 83 and RM 88 is an area of significant change exhibited in 1993. Large sand and cobble bars were built by the high flows and the channel moved substantially. Since backwaters form downstream of these sand bars, these transects were located to better understand the development of the bars and associated backwaters under different flow conditions. The reach between RM 0 and RM 14 is in the backwater area from Lake Powell. This reach is not like any other reach in the river. The gradient is low, the channel meanders between sand bars and shoals within the limit of the canyon walls and substantial areas of low velocity habitat exist at low flow relative to other river reaches. These transects will provide data to document the relative permanence of these backwaters. The locations of these transects are shown in Figures 3.2 through 3.4. Table 3.6 summarizes the transect surveys completed during the last 7 years, including the date of the first survey.

The RT and Clay Hills cross-sections were analyzed to determine local deposition and scour and change in average bed elevation with time. The change in percent cobble in the substrate with time was also analyzed. The same analyses were performed for the mixer and debris field transects, but in this case the change was analyzed for the four measurements taken over the runoff period and compared to the volume of flow and peak discharge for each period. This more detailed sampling of the mixer and debris field transects was conducted during the period 1994 - 1996. In 1997 the sampling frequency was decreased to twice yearly. In 1998, in an effort to transition from research to long term monitoring and reduce cost, measurement of all cross-sections was completed only after runoff in August.

Channel Response to Flows at USGS Gage Locations

To assess the changes seen at the surveyed transects during the 7-year study period against long term change, data collected at USGS gaging sites on the San Juan River were examined to determine changes in cross sectional area with time. The stations at Bluff, Shiprock, Farmington and Archuleta were selected for analysis.

At each station, field discharge notes were obtained for the period of record. The field discharge notes contain distance-depth data which were used to plot the river bed profile in an attempt to determine changes with time. It is important to note that in plotting these data, all distances to the river bed are taken from the water surface, which obviously fluctuates with stage. When the location of data collection for the rating measurements is sufficiently close to the gage datum, then these data can be corrected to a fixed datum. When that is not the case, some other means of control, such as a fixed point of the river bottom on bedrock, is required.

All extracted data were digitized and plotted to determine change in cross section with time. The change in average channel cross sectional area from an arbitrary datum was plotted against time to determine the state of the river (scour or deposition) over time.

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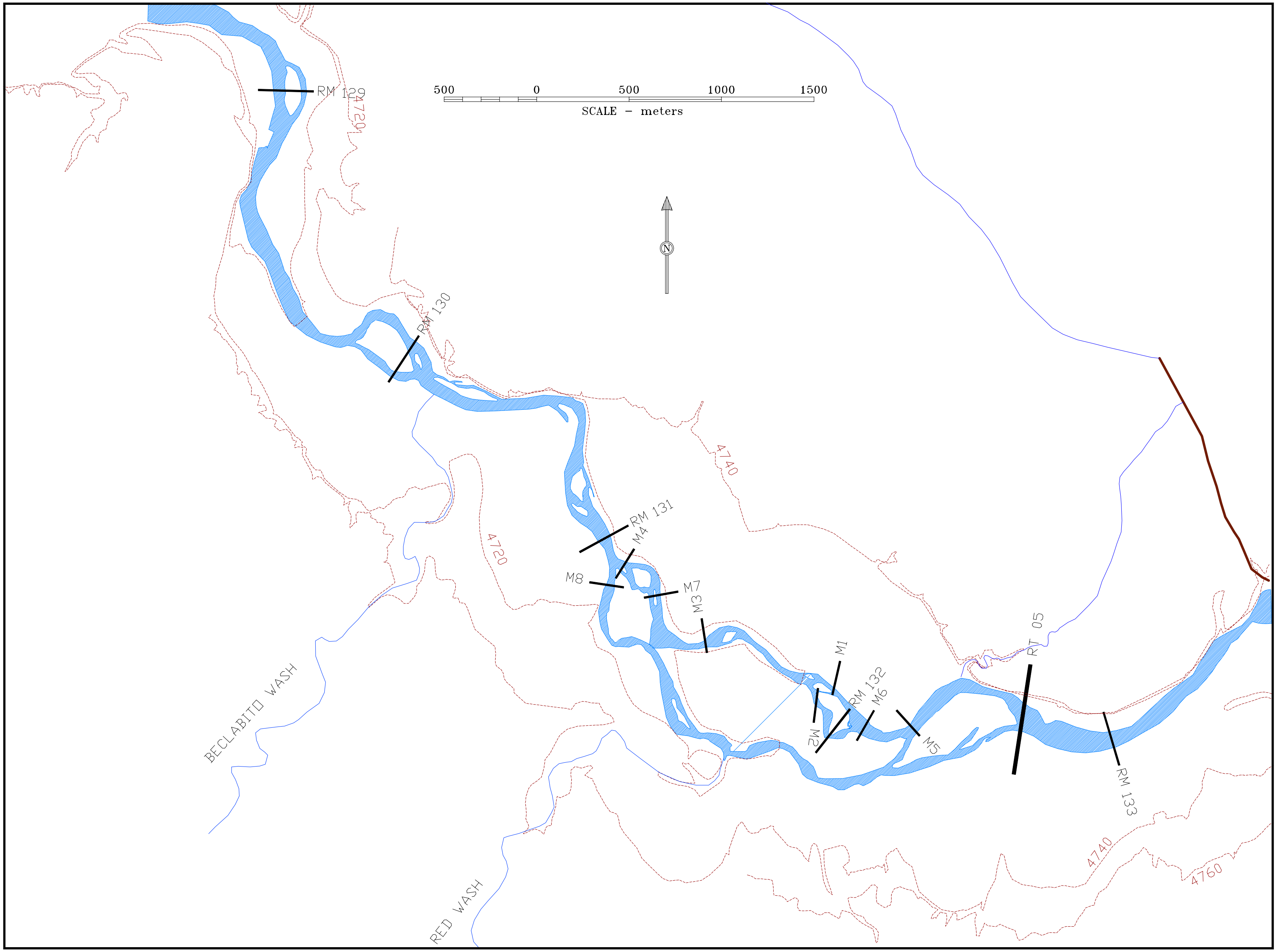

Figure 3.2. San Juan River Transect Locations in the "Mixer" Detail Reach

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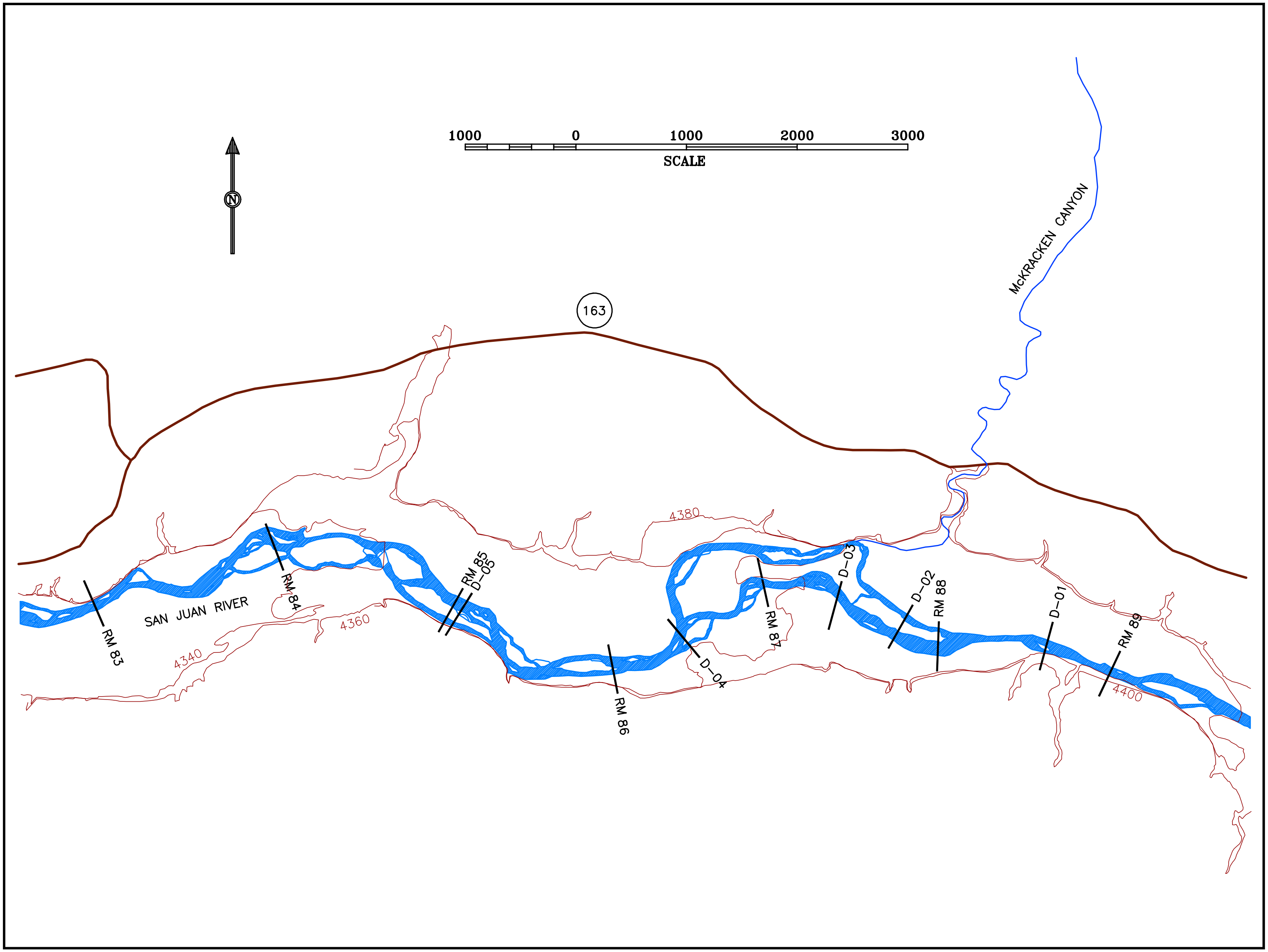

Figure 3.3. **San Juan River Transect Locations in the "Debris Field", RM 83 to RM 88**

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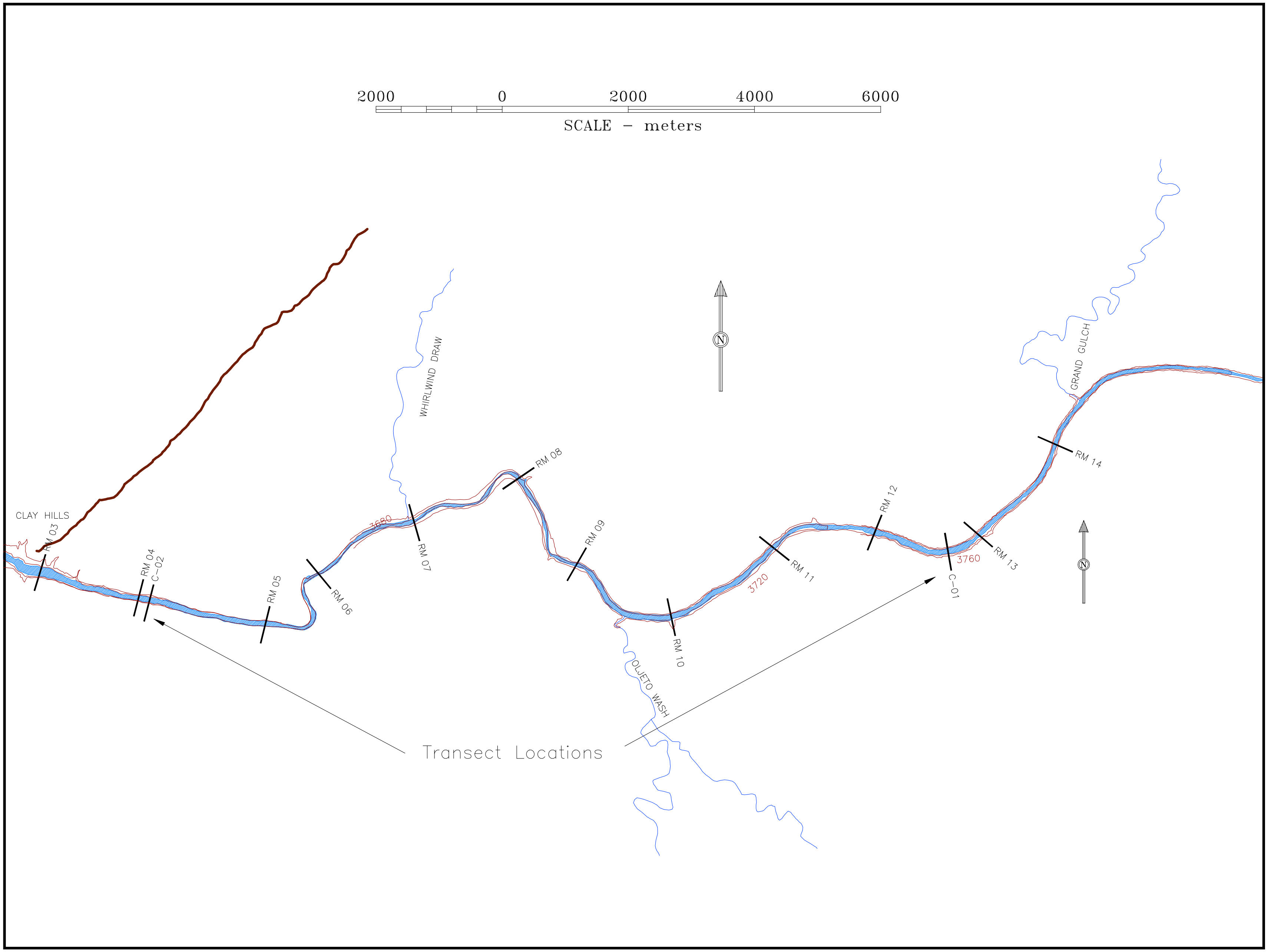

Figure 3.4. San Juan River Transect Locations, RM 0 to RM 14

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Table 3.6. Transect survey locations and summary of completed surveys.

Transect	Geo-morphic Reach	River Mile	First Survey Date	Number of Surveys Completed	Location Description
RT-01	6	168.30	March 17, 1992	14	Fruitland
RT-02	5	154.40	March 17, 1992	13	below Hogback
RT-03	5	142.70	March 17, 1992	13	Shiprock
RT-04	5	136.60	March 17, 1992	13	below Cudei
RT-05	5	132.70	March 18, 1992	13	upstream of mixer
RT-06	4	124.00	March 18, 1992	13	upstream of Mancos
RT-07	4	122.10	March 18, 1992	13	downstream of Mancos
RT-08	3	104.30	March 18, 1992	13	Aneth
RT-09	3	90.80	March 19, 1992	13	Montezuma Creek
RT-10	3	82.30	March 19, 1992	13	Bluff
RT-11	3	70.00	March 19, 1992	13	Combs Wash
M-01	5	131.90	February 20, 1993	15	Mixer
M-02	5	131.85	February 22, 1993	21	Mixer
M-03	5	131.50	February 21, 1993	21	Mixer
M-04	5	131.10	February 21, 1993	18	Mixer
M-05	5	132.30	September 21, 1993	19	Mixer
M-06	5	132.10	September 21, 1993	18	Mixer
M-07	5	131.30	September 21, 1993	17	Mixer
M-08	5	131.20	September 21, 1993	18	Mixer at Redwash
D-01	3	88.50	September 22, 1993	18	Debris Field
D-02	3	87.50	September 22, 1993	18	Debris Field
D-03	3	87.20	September 22, 1993	16	Debris Field
D-04	3	86.20	September 23, 1993	18	Debris Field
D-05	3	83.00	September 23, 1993	18	Debris Field
C-01	1	12.70	October 28, 1993	10	Grand Gulch
C-02	1	4.10	October 29, 1993	10	Clay Hills

Flow Modification Impact on Channel Complexity

Modification of the flow regime to restore more natural spring runoff after 30 years of altered flows as a result of the operation of Navajo dam could cause a change in channel complexity. To examine the impact of the altered flow regime on overall channel morphology, channel complexity, as measured by changes in total number of islands within each reach, was analyzed using habitat mapping coverage in a geographic information system (GIS). Only Reaches 3, 4, and 5 were used in this analysis because mapping for these reaches was the most temporally comprehensive throughout the 7-year research period than the upstream reaches, and Reaches 1 and 2 have no islands because of canyon restraints. Channel complexity was analyzed in two ways: the overall correlation between discharge and number of islands, and the chronological effect of flow regime on island count during the 7-year research period.

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It has been hypothesized in the SJRIP that secondary channels are an important component of the aquatic habitat in the San Juan River (Propst, 2000). If channel scour caused a reduction in islands, secondary channels would be lost. Monitoring island count with time allows assessment of this potential for channel simplification. To assess the impact on habitat diversity, the trend of habitat diversity was also examined for this time period during low flow conditions. Habitat diversity was assessed by computing the Shannon-Weaver habitat diversity index (Shannon and Weaver, 1963) by river mile for each habitat sampling run. The index is computed as

$$SWI = -\sum_{i=1}^{n} \frac{count_i}{totalcount} \cdot \log(count/totalcount)$$

Where

SWI	=	Shannon-Weaver Index
n	=	number of habitat categories (31)
$Count_i$	=	number of habitats of the i^{th} category in the river mile
Total count	=	the total number of habitats in the river mile

The index increases with increased diversity, reaching a maximum of 1.49 (log of 31) for the categories mapped in the San Juan. Only the wet habitat categories are included in the analysis.

Bankfull Channel Capacity

In 1996, four single-channel reaches about 0.4 km in length containing five cross-sections each were surveyed between RM 133 and RM 174. Flow in these reaches was modeled using the U.S. Army Corps of Engineers flow model, HEC-RAS. The model was calibrated to surveyed water surface profiles over a range of flowrates at each model reach and the roughness coefficient calibrated for the model. Bankfull flows were predicted to begin when one of the five cross-sections exhibited out-of-bank conditions.

Since the RT series were first surveyed prior to research flows and have been surveyed twice annually since that time, an assessment of channel capacity and the change in channel capacity was made, using the calibrated roughness coefficient from the modeled reach and applying the Manning equation:

$$Q = (w\, d^{5/3}\, S^{1/2})/n$$

Where

Q = discharge, cfs
w = width, ft
d = average depth, ft
S = water surface slope, ft/ft

and

n = roughness coefficient

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Since water surface elevations were surveyed each time the cross-sections were surveyed, sufficient information was available to allow calculation of water surface slope. The survey with the greatest flow (1,170 to 1,950 cfs, depending on the date of survey) was selected as the calculation closest to the bankfull condition for purposes of slope computation. Using the calibrated roughness coefficient of 0.027, the Manning equation was solved for slope, knowing flow, width, and cross-sectional area from the surveys. Bankfull flow at each cross-section for spring 1992 and fall 1997 surveys was then computed, assuming that the gradient did not change.

Cobble Bar Characterization

The production of clean cobble for spawning areas is dependent upon entrainment of cobble during high flow periods just prior to spawning and deposition of the cobble under conditions that allow it to be placed relatively cleanly, without significant sand and fines to fill the interstitial spaces. An important part of determining flow requirements for the endangered fish species is an understanding of the conditions required to entrain cobble of the size necessary for proper spawning. To fully understand the process, the size of the substrate to be moved and the hydraulic conditions required to move it must be determined and compared to the conditions that exist at critical locations in the river.

Characterization of Bed Material in Suspected and Potential Spawning Bars

Suspected spawning bars in the San Juan River were identified from radio tracking of adult squawfish during the summer of 1994. During the fall of 1994, thirteen sites were identified that had visual similarity to the sites utilized during spawning in 1993 and 1994. After normal spawning time was over, multiple samples of substrate material were measured at each of the sites. Table 3.7 summarizes and describes these locations. From this list of sampled sites, a subset of 4 sites was selected that represented conditions that were thought to be most suitable for spawning or had exhibited use during spawning time in the past. These locations were studied in more detail for an extended period of time. The selected sites for extended study are indicated in Table 3.7.

At each site, samples were collected in a linear or cross-sectional pattern, usually within or across the chute. At multiple locations parameters included: pebble counts and depth to embeddedness. Particles larger than 1 cm were measured utilizing the point count method (Wolman 1954) in the same vicinity. Size-frequency plots were prepared for both the cobble and interstitial material. Only the material 1 cm or greater in diameter was included in the frequency analysis, with the assumption that this larger material formed the bar structure, with the smaller materia being interstitial. Prior to 1998, the intermediate cobble cross-sectional diameter was used as the size designator. In 1998, an aluminum plate was prepared with square openings of from 1 cm to 10 cm in 1 cm increments and in 2 cm increments from 10 to 20 cm, representing equivalent sieve sizes. Cobble larger than 20 cm is measured as in previous years. A correlation between intermediate diameter and sieve size was completed to understand the relationship between the two measurement methods and to adjust previous years' data to equivalent sieve sizes for better consistency, provided a significant difference was found.

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Table 3.7. Cobble bar sampling locations.

Location	Geomorphic Reach	Description	Years Sampled
RM173.7	6	Upstream end of tributary debris bar*	1995, 96, 97, 98
RM172	6	Upstream end of mid-channel bar	1995, 96
RM169	6	Middle chute of mid-channel bar	1995,96
RM168.4	6	Three chutes (N, M, S) below mid-channel island*	1995, 96, 97, 98
RM163	6	Upstream end of mid-channel bar	1995, 96
RM137.7	5	Upstream end of secondary at large mid-channel bar complex	1995
RM137.3	5	Upstream end of point bar below mid-channel bar complex	1995
RM132	5	Main Bar suspected spawning location in 1993, 1994 (compare to Sites 1 and 3 from previous studies)*	1994, 95, 96, 97, 98
RM131.2-RW	5	Red Wash bar 1993 spawning site (compare to Site 4 from previous studies)	1994, 95, 96
RM131.2 Main	5	Main Channel Bar suspected spawning site, numerous fish contacts in 1994 (Compare to Site 5 from previous studies)*	1995, 97, 98
RM 109.8	4	bar at upper end of island. Radio-tagged fish location in 1995 during spawning	1995
RM 88	3	Small bar on inside curve in active area of river	1995
RM 82	3	Three chutes in debris area RM 81.85, 81.9 & 81.95	1995
RM 78	3	Chute at upper end of island	1995
RM 76.6	3	Chute at confluence of secondary & main channel above Sand Island Boat Ramp	1995

* Extended period study sites.

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A similar set of data was collected in 1994 on the Colorado River (RM 168.8) where Colorado pikeminnow were found adjacent to a newly formed cobble fan. The same sample methodologies were utilized at this site. Bed material size distribution from all sites was compared to similar bed material size distribution from a known spawning bar at RM 16.5 on the Yampa River (Harvey, et al. 1993). This comparison was made as a check on the probability of the material found being suitable for spawning of Colorado Squawfish.

Depth of Open Interstitial Space in Cobble Bars

One of the important conditions for a cobble bar to be suitable for spawning is adequate depth of clear interstitial space or depth to embeddedness. Several methods of obtaining a measure of cobble bar embeddedness have been described in the literature. Platts, et. al. (1983) describe a method of assessing embeddedness that estimates the portion of the surface area of the larger size particles in a bar that are covered with fine sediments, giving a rating system from 1-5 to describe the degree of embeddedness. Unfortunately, the method does not deal with the issue of the depth to embedded material.

McNeil (1964) described a sampling method utilizing a single tube worked into substrate material to retrieve a sample of the substrate, but the method extracts a disturbed core and does not allow measurement of the open interstitial space.

Cryogenic sampling methods (freeze core) have been developed utilizing both single and multiple tubes that allow an assessment of open interstitial space as well as substrate material size (Everest, et. al (1980). The method is effective but is material and labor intensive, limiting the number of samples that can economically be collected. The method was tried and found to be too cumbersome to allow characterization of large areas.

The method settled upon is that described by Osmundson and Scheer (1998) where a measurement to the embedded layer is made by working a hand between the larger particles of a bar until sand is encountered and measuring the depth from the top of the surrounding cobble to the point that sand is contacted. The method was first developed for application in this study and employed and reported by Osmundson and Scheer (1998). The method is fast and requires minimal training and equipment to perform. Many measurements can be taken in a short period of time and underwater sampling is possible. To allow comparative evaluation of numberous bars and to assess variation on an individual bar, this method is superior to other methods examined.

The cobble bars from which substrate measurements were made were also sampled for the depth to the embedded layer (open interstitial space). Each cobble bar was sampled on a 0.7 to 1.3 meter grid. The depth from the top of the cobble to a point at which the interstitial space was filled with sand was measured at each point (depth to embedded layer). Each sample point was surveyed with a total station to determine relative x,y position and elevation. These measurements were then plotted in a three-dimensional surface plot to allow assessment of the variation in depth. In addition, a frequency distribution of depth to embeddedness was prepared for each site.

Topographic Changes in Cobble Bars

One suspected and two potential spawning bars were surveyed with total station survey equipment with local horizontal and vertical control. The suspected bar at RM 132 was surveyed from 1995 through 1998. The potential bars at RM 173.7 and RM 184.4 were surveyed from 1996 to 1998. Three-dimensional surface plots were prepared for each survey. Changes between survey dates were determined by subtracting the previous surface from the present surface. These changes are also shown as three-dimensional surface plots.

Cobble Transport Analysis

For long-term cobble bar formation and maintenance, the system must be capable of transporting an adequate size and quantity of cobble into the appropriate areas. In addition to assessing bankfull discharge at channel cross-sections, the study reaches described in Section Bankfull Channel Capacity were modeled to determine the discharge necessary to transport cobble through the intervening low-gradient reaches between bars. The method employed to determine this relationship involved examining critical dimensionless shear stress (Shield's stress), a parameter estimating the pressure applied to the bed substrate by the overflowing water velocity and depth, for the existing bed material. Incipient motion (the point at which particles begin to move) of the median particle diameter (D_{50}) of bed material is theorized to occur when the critical shear stress, $J^{*}_{c50,}$ is in the range of 0.02 (Andrews 1994) to 0.03 (Parker et al. 1982). This value varies from river to river and may even fall outside this range. Under conditions of incipient motion, the gravel just begins to move slightly and transport rates are very low (Pitlick and Van Steeter 1998). As the dimensionless shear stress increases, the number of bed particles in transport increases rapidly. By the time the dimensionless shear stress reaches 0.06 (Andrews 1994), a majority of the particles on the bed's surface are in motion. Appreciable transport will occur at condition of average motion, where most particles can be moved, but at a moderate rate. Andrews (1994) found transport of particles as large as the 80th percentile with dimensionless shear stress in the range of 0.032 to 0.042. The three conditions of transport examined in this study are initial or incipient motion (J^{*}_{c50} = 0.02 to 0.03), average motion (J^{*}_{c50} = 0.030 to 0.045), and full motion (J^{*}_{c50} = 0.045 to 0.060).

Low Velocity Habitat Creation and Maintenance

An understanding of the formation and stability of low velocity habitat in the system is important to an evaluation of the nursery habitat availability and the conditions necessary to produce and maintain the habitat. In the late summer of 1994, three sand/cobble bars in the lower river were topographically surveyed with a total station, registering the survey to permanent control at each site. The bars selected were typical of those that form with good backwater potential behind the bar. Each bar was surveyed again in each subsequent year as a comparison to the 1994 data and to relate change to hydrology. Table 3.8 lists the location and survey dates of each of the bars surveyed.

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Table 3.8. Sand/cobble bar survey locations and dates.

Description	Location - RM	Survey Dates
Debris Field 1, River Right	88.1	8/24/94, 10/7/94, 3/5 /95, 8/14/95, 10/12/95
Debris Field 2, River Left (includes D-4 Transect)	86.4	8/24/94, 10/7/94, 3/5/95, 3/14/95, 10/12/95
Clay Hills (at C-2 Transect)	4.1	8/25/94, 10/6/94, 3/4/95, 3/15/95, 10/13/95

Three-dimensional plots were prepared for each survey and the surfaces of the two surveys compared to document change. The change was analyzed in terms of the intervening hydrograph. River stage also plays a large role in availability of backwaters. Where possible the stage/backwater area relationship for these sites was examined in the 14 to 28 m^3/sec (500 - 1,000 cfs) range. Stage-discharge data were not available to extrapolate the range of flows beyond that shown. In some cases the bed elevation had changed too greatly to allow development of a stage discharge relationship at a particular site.

These main channel bars support only a small percentage of the backwater habitat in the San Juan River. A large portion of the backwater habitat occurs at the mouths of secondary channels after flow recession. These backwaters require periodic flushing for long term maintenance. To measure flow conditions necessary to maintain backwaters, two ephemeral secondary channels that form backwaters were selected for surveying and modeling. The first is located on river left just downstream of the Montezuma Creek Bridge (RM 93 to 93.5), and the second is approximately 1.6 km upstream of Sand Island Campground (RM 77.3 to 77.5) on river left. These backwaters have formed each year during base flow (low, stable, non-storm effected flows between spring runoff events) conditions, indicating relative stability, although the size and depth of the backwaters have varied.

These reaches were surveyed in detail in 1996. During that year, flow conditions were inadequate to flush these backwaters (Figure 2.5). A total of 10 surveys were completed in 1997, beginning on May 13 and continuing through August 19. During that time, a correlation between secondary and main channel flow was developed to predict flow in the secondary channels. Suspended sediment concentration was measured about twice weekly during this time to provide data for later modeling.

Suspended Sediment Analysis

Sediment Sampling

A suspended sediment sampling program was implemented in March 1992 for sites on the San Juan and it tributaries. A DH-59 depth integrating suspended sediment sampler was used with the "equal transit rate method of sampling." This method requires that samples are collected at equally spaced

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verticals in the flow cross section. The transit rate of the sampler must be uniform and the same in all verticals. The composite sample from all verticals represents the mean suspended sediment concentration. Laboratory analysis determines the sediment concentration in mg/l.

Ecosystems Research Institute, Inc. in Logan, Utah has done all the suspended sediment analysis to date. EPA Method 160.2 was used. This method consisted of filtering a small volume, typically 25 ml or less, of sample though a previously weighed 40 to 60 micron glass fiber filter. The filter was dried in an oven at 103 to 105/C for one hour. It was then put in a desiccator to cool for 24 hours. The filter was re-weighed. The weight difference is the mass of suspended solids in the sample. Dividing the mass of the solids by the original volume of filtered sample yielded the concentration in mg/l.

Beginning in 1995, intermediate sampling twice per week was added to better assess sediment inflow during intervening storm events. These intermediate samples were single point samples in each cross-section, correlated to the full sample sets at the cross-section for interpretation of results. Samples were taken from the locations and on the dates shown in Table 3.9.

A review of the sediment data collected since 1992 indicates that a number of the sampling data points were influenced by storm events. Sediment concentration/flow relationships were examined for full data sets and those filtered to remove storm influenced data points. In addition, the sediment discharge relationships for each site during the ascending and descending limb of the hydrograph were analyzed. The suspended sediment concentration and grain size distribution was used in the sediment transport analysis for backwater flushing.

Sediment Transport Analysis

Sediment transport analyses were completed to characterize cobble transport/flow relationships for maintenance of cobble bars. Fine sediment transport modeling was conducted to study the mechanisms of backwater flushing in typical backwaters. The methods and results of these studies are reported in the San Juan River Basin Recovery Implementation Program Flow Recommendation Report now in print. The results are not reproduced here, although the data collection and analysis were a part of these studies.

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Table 3.9. Sediment sample locations and number of samples taken each year.

Location	1992	1993	1994	1995	1996	1997	1998
San Juan River at Lee Acres Bridge	5	6	6	7	5		
San Juan River at Farmington*	5	6	6	7	5	8	6
San Juan River at Fruitland	5	6	6	7	5	8	6
San Juan River at Shiprock*	5	6	6	7	5	8	6
San Juan River at Four Corners*	5	6	6	7	5	8	6
San Juan River at Montezuma	5	6	6	7	5	8	6
San Juan River at Bluff	5	6	6	7	5	8	6
San Juan River at Mexican Hat	5	6	6	7	5	8	6
Miller St. Animas	5	6	6	7	5	8	6
La Plata River		4	2	5	5	8	4
Red Wash		1	1	4			
Mancos River		4	3	6	3	8	6
McElmo Creek		6	6	7	5	8	6
Montezuma Creek Wash		2	2	5			1
Cottonwood Wash		1	1	5			
Arroyo 46.9		2		5			
Combs Wash		1		5			
Chaco Wash				6	2	3	5
Chinle Wash				4		5	4
* Spot sampling at these sites				37	36	48	44

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RESULTS

Historic Analysis of Fluvial Morphology

Table 3.10 summarizes the bankfull water surface area, island count and island area by geomorphological reach for the four time periods analyzed. The data are also summarized for all reaches analyzed and for reaches three through six, the critical habitat reaches.

In the 1930's the San Juan River, especially in the lower reaches, was a broad, heavily braided sand bottomed river with little vegetation. This is particularly true for Reach 3, where the river is over 1,000 m wide in several locations, with an average width of 472 m. This period was preceded by some very large fall floods in 1991 and 1927. The gage was not established in 1911, but the stage at Shiprock during this October storm event was 6.7 m.. After gage establishment a peak discharge of 80,000 cfs on 11 Aug 1929 produced a stage of 1.75 m, so it is estimated that the discharge in 1911 was well over 100,000 cfs. In 1927, a flood of 70,000 cfs was reported at Bluff. In 1929, a peak flow of 80,000 cfs was measured at Shiprock. It is hypothesized that these large floods, the result of high intensity thunder storms and extensive lower basin runoff, deposited large quantities of sand in the river, particularly in the lower reaches, accounting for the broad, sand bottomed river.

Between the 1930 and the 1950 data sets, channel surface area decreased by 21% in the critical habitat area. Island count dropped by 36% during the same period, but island area increased by 22%. Reach 3 exhibited the greatest decrease in bankfull channel surface area and the greatest increase in island area, although the number of islands decreased somewhat. Reach 7 exhibited the least change in surface area. While the overall island area increased, the three uppermost reaches decreased in island area while the three lower reaches increased.

The most noted difference between the 1930 and 1950 data sets was the increase in riparian vegetation. This is partly due to natural re-vegetation after the earlier floods and the appearance of tamarask for the first time in the basin. Between 1937 and 1950, the greatest magnitude flood was 42,500 cfs (daily mean flow), with five years having mean daily peak flows above 20,000 cfs. Based on the sediment studies conducted during this period (Thompson, 1982), these floods appear to be less sediment laden than the earlier large magnitude events. The average annual sediment load between 1930 and 1942 was 47,200,000 tons per year. Between 1942 and 1973, the average dropped to 20,100,000 tons per year, with the major shift occurring in 1942. With lower sediment concentrations and high flow magnitudes, it was possible for these floods to transport large quantities of sand out of the system. The combination of an increase in riparian vegetation and decrease in sediment load lead to the narrower river. Large islands formed in the lower portion of the river as the channel incised and the islands vegetated.

Between the 1950 and 1960 data sets, the bankfull channel surface area decrease by an additional 6% with the 1930's data set as a base. The number of islands decreased by an additional 28% and the island area decreased dramatically to just 29% of the area in the 1930's. All reaches exhibited this dramatic change in island area while only reach three decreased in channel surface area.

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Table 3.10. Summary of historic aerial photography analysis of changes in channel morphology of the San Juan River from four periods, 1934-35, 1950-52, 1959-62 and 1986-88.

Reach	3	4	5	6	7	8	Total	3-6 sum	3-6 % of
RM	67 - 104	105-130	131-154	155-180	181-213	214-224	67-224	67-180	1930's
Bankfull Channel Surface Area - m^2									
1934-35	28,873,702	12,419,696	11,060,156	6,478,302	10,528,228	2,042,540	71,402,624	58,831,856	
1950-52	19,686,966	11,551,580	10,121,519	5,019,738	10,380,251	1,834,507	58,594,560	46,379,802	79%
1959-62	15,879,905	11,392,510	10,023,784	5,610,641	10,358,396	1,654,169	54,919,404	42,906,840	73%
1986-88	6,774,785	11,010,636	9,774,228	3,972,724	10,301,457	1,452,946	43,286,776	31,532,374	54%
Island Count - number									
1934-35	133	101	229	153	209	24	849	616	
1950-52	125	84	135	49	142	24	559	393	64%
1959-62	42	53	70	56	70	4	295	221	36%
1986-88	191	125	149	97	140	36	738	562	91%
Island Area - m^2									
1934-35	3,785,916	2,026,358	6,697,942	3,685,329	4,465,273	380,616	21,041,435	16,195,546	
1950-52	6,312,228	2,841,759	8,308,199	2,215,718	3,056,857	112,696	22,847,457	19,677,904	122%
1959-62	1,432,291	978,474	2,131,334	222,963	1,091,938	74,360	5,931,360	4,765,063	29%
1986-88	3,558,910	2,597,722	5,859,658	1,236,571	1,860,320	657,279	15,770,460	13,252,861	82%
Mean Bankfull Width - m									
1934-37	472	297	312	155	198	115	284	326	
1950-52	322	276	286	120	195	104	233	257	79%
1959-62	260	272	283	134	195	93	219	238	73%
1986-88	111	263	276	95	194	82	172	175	54%

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The riparian vegetation is even more dense in the 1959-62 data set than earlier and the bankfull channel is much simplified. Many of the secondary channels that were clean in the 1950 photography are heavily vegetated. During the period between the 1950-52 and 1959-62 data sets, the maximum daily peak discharge was 26,000 cfs in 1957, with no other values above 20,000 cfs and only two others above 10,000 cfs. Cumulatively, this is the driest decade on record. This reduction in flow in conjunction with the increase in riparian vegetation (tamarask were well established in the system by this time) likely resulted in the vegetation of the secondary channels and the loss of channel complexity.

Between the 1959-62 and 1986-88 data sets the channel surface area decreased by an additional 19%, with most of the change in reaches three and six. The number of islands dramatically increased, reaching 91% of the 1930's abundance. Island area also recovered to 82% of the 1930's level.

Navajo Dam began regulating the San Juan River in 1962. With this regulation came a further reduction in flood flows, but an increase in base flows. The mean annual peak flow is 10,160 cfs for this period, compared to 10,900 cfs for 1950-1961 period and 17,775 cfs for the 1935-1950 period. The maximum daily average flow for this period was 26,700 cfs in 1973. The impact of regulation is evident when examining the peak discharge in relation to the total annual runoff for the three periods. The peak discharge is about the same for the periods 1950-1961 and 1962-1988, while the latter period had an average annual runoff of 1.7 million acre-feet and the earlier period only 1.4 million acre-feet.

The other noted change in the basin during this 1960 to 1988 time period is the introduction of Russian olive into the basin. Survey notes from 1962 never mention Russian olive, while every stream channel and old secondary channel in the basin is now heavily vegetated with Russian olive. It is the dominant vegetation type, especially in areas of channel braiding an broad flood plains. During high flow, the riparian Russian olives dislodge and form debris piles in the river. At low flow these debris piles form islands and rapidly vegetate. During the next flood flow, they accumulate sediment and grow, becoming islands. This process is thought to have heavily influenced the increase in islands and added to channel complexity since the 1960s.

Channel cross-section surveys completed in 1962 and 1993 show that the channel has narrowed and deepened slightly during this time period (Bliesner and Lamarra, 1994) consistent with the findings of the aerial photography comparisons.

In addition to the changes in flow and vegetation, a second shift in the cumulative sediment plot came in 1973 with a further reduction in sediment load from an average of 20,100,000 tons per year to 10,100 tons per year. All of these changes have resulted in a much different channel than existed in the 1930's. While regulation of the flows with Navajo dam have had an influence on these changes, that influence has likely not been as great as that of the change in sediment load, natural hydrology and riparian vegetation.

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Figures 3.5 through 3.8 present aerial photographs of an area in Reach 3 from RM 84 to RM 86 taken in 1934, 1952, 1961 and 1988. The sequential change discussed in this section can be seen by comparing these four photographs. Although the flowrates are not the same for all photographs, the conditions of the bankfull channel and the differences in vegetation can be noted. Vegetation was established and the channel became much more defined between 1934 and 1952, but the greatest change in vegetation occurred between 1961 and 1988. There was relatively little change between 1952 and 1961 for this location.

Geomorphological Characterization

River Valley Geometry

The distribution of valley width by river mile from the confluence of the San Juan River with Lake Powell to Navajo Dam is shown in Figure 3.9. The mean valley width per mile was computed as the valley area divided by the length, placing the river mile perpendicular to the general river trend where the river mile crossed. The data are presented as 3-mile running averages. The upper reach of the river from Navajo Dam to about RM 208 is canyon bound. The valley then broadens down to about Farmington, where it is constricted by bedrock on either side of the river. Between Farmington and Shiprock the valley broadens. The broadest area of the valley is just below Shiprock. From RM 140 to RM 127 the valley narrows to about ½ its width through the main irrigated area and remains at this general width (about 1,000 meters) until entering the canyon at the confluence with Chinle Creek. Below this point it is about 1/20 its width in the main irrigated area. It should be noted that the width may be somewhat overestimated in the irrigated areas due to difficulty in interpreting the boundary of the alluvial valley. The slopes to the river are more gradual and the signatures on aerial photography masked because of the irrigation. While the area may be somewhat over stated in this reach, the general trends hold.

Channel Contact Geology

The distribution of river cutbanks and the material makeup of these cutbanks is shown in Figure 3.10. The top of the area plot for cobble represents the total length of cutbanks per mile on a 3-mile running average basis. The value is the sum of both sides of the river so it is theoretically possible to have more than one mile of cutbank per mile of river. The values for sand, cobble and gravel are weighted to account for areas that are uniformly sand, gravel or cobble as well as those areas that contain sand, gravel or cobble, such as areas of sandy cobble or gravelly sand.

The other category of geologic contact is bedrock (including talus slope). The length of bedrock contact per mile of river is shown as the top area on Figure 3.10. The value is the difference between the top and bottom of the area graph for bedrock.

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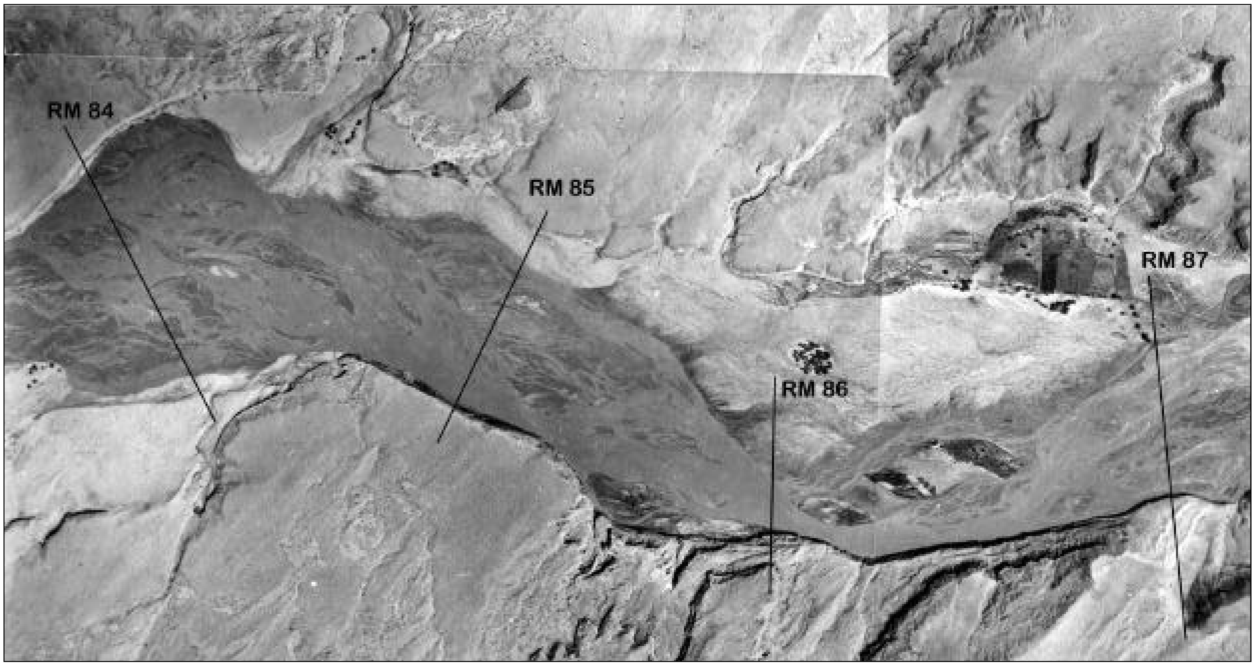

Figure 3.5. **Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1934.**

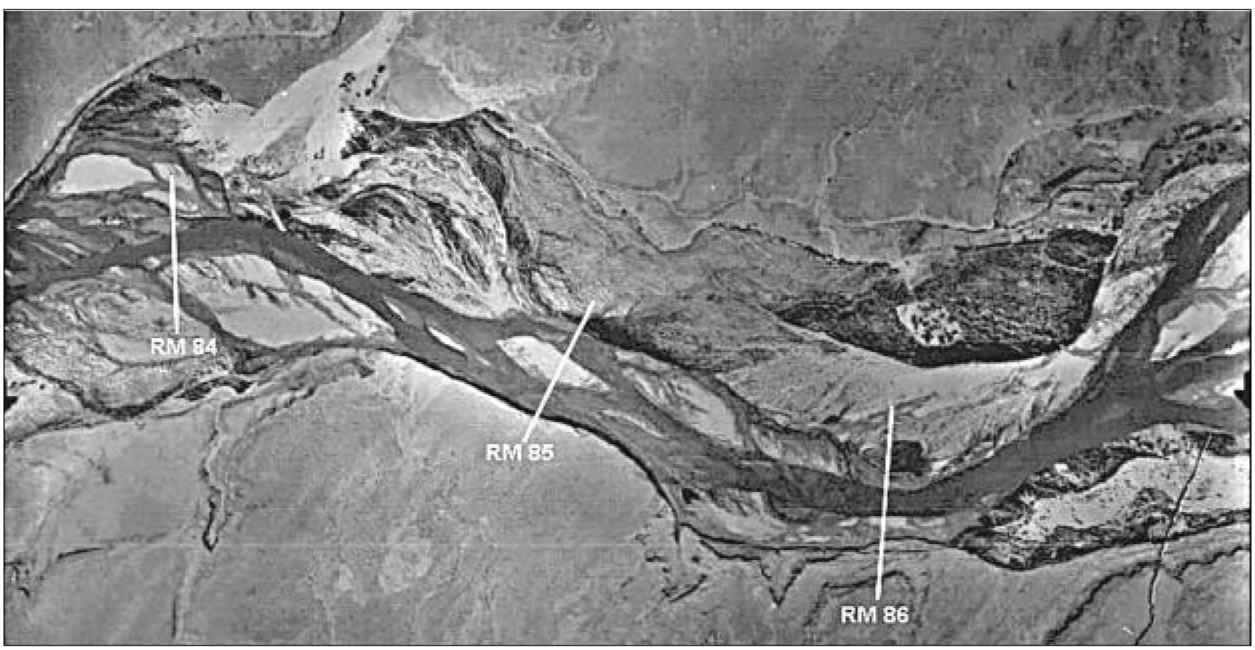

Figure 3.6. **Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1952.**

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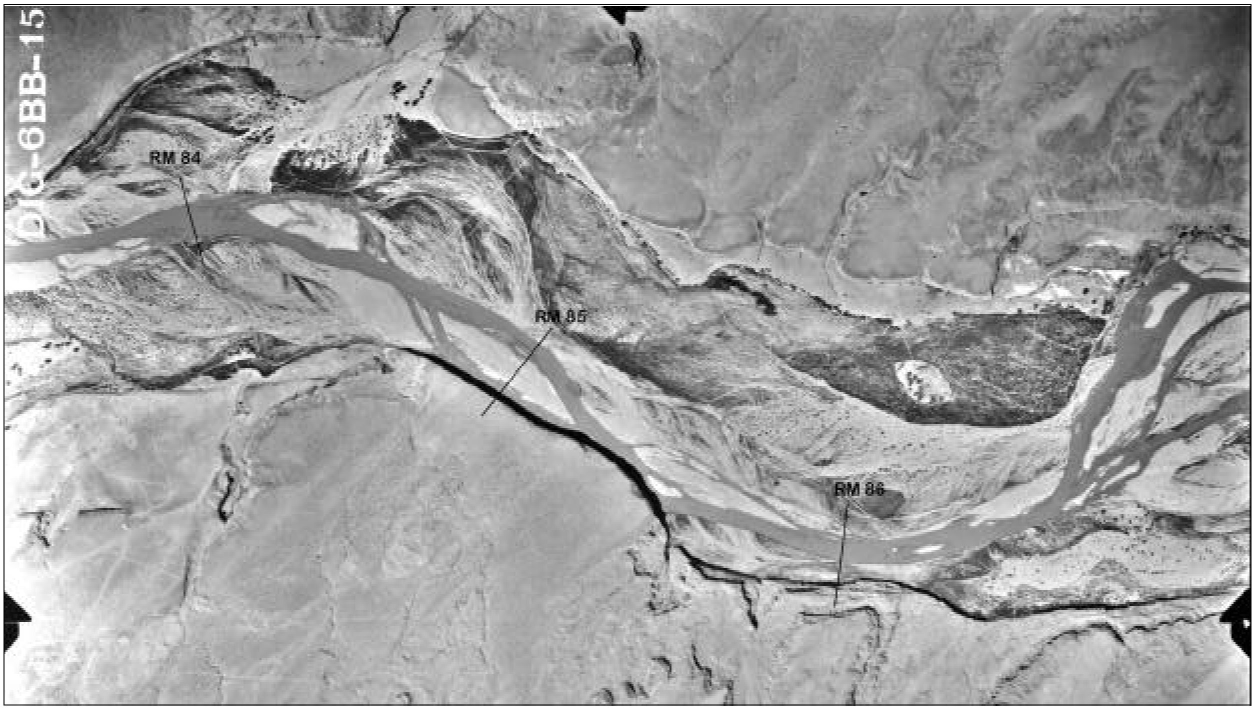

Figure 3.7. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1961.

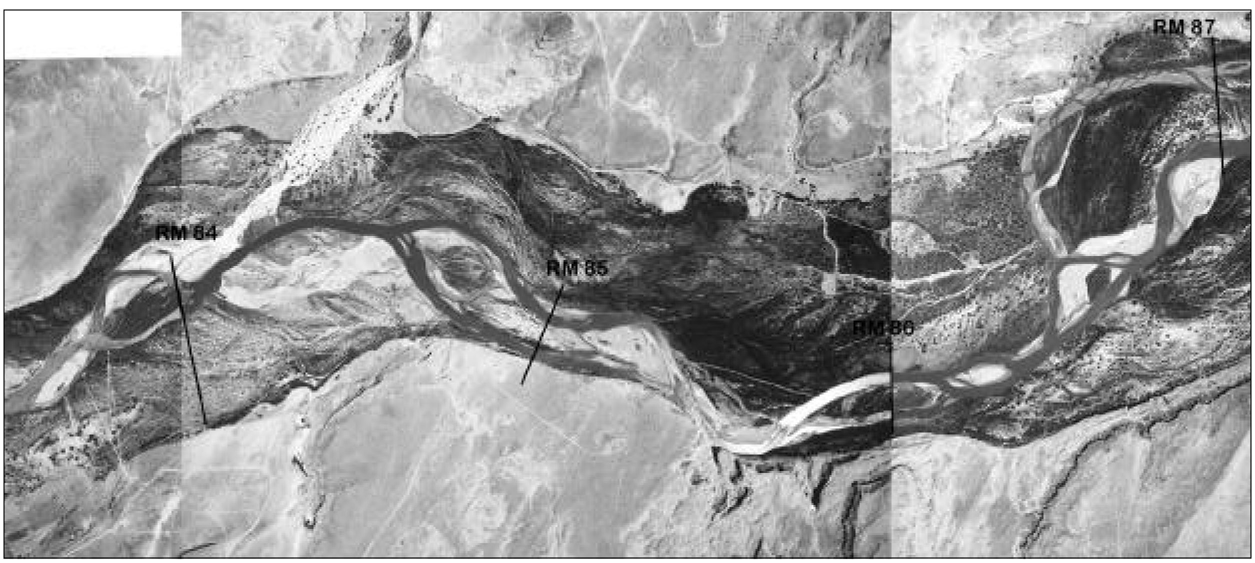

Figure 3.8. Aerial photograph of the San Juan River between RM 84 and RM86 taken in 1988.

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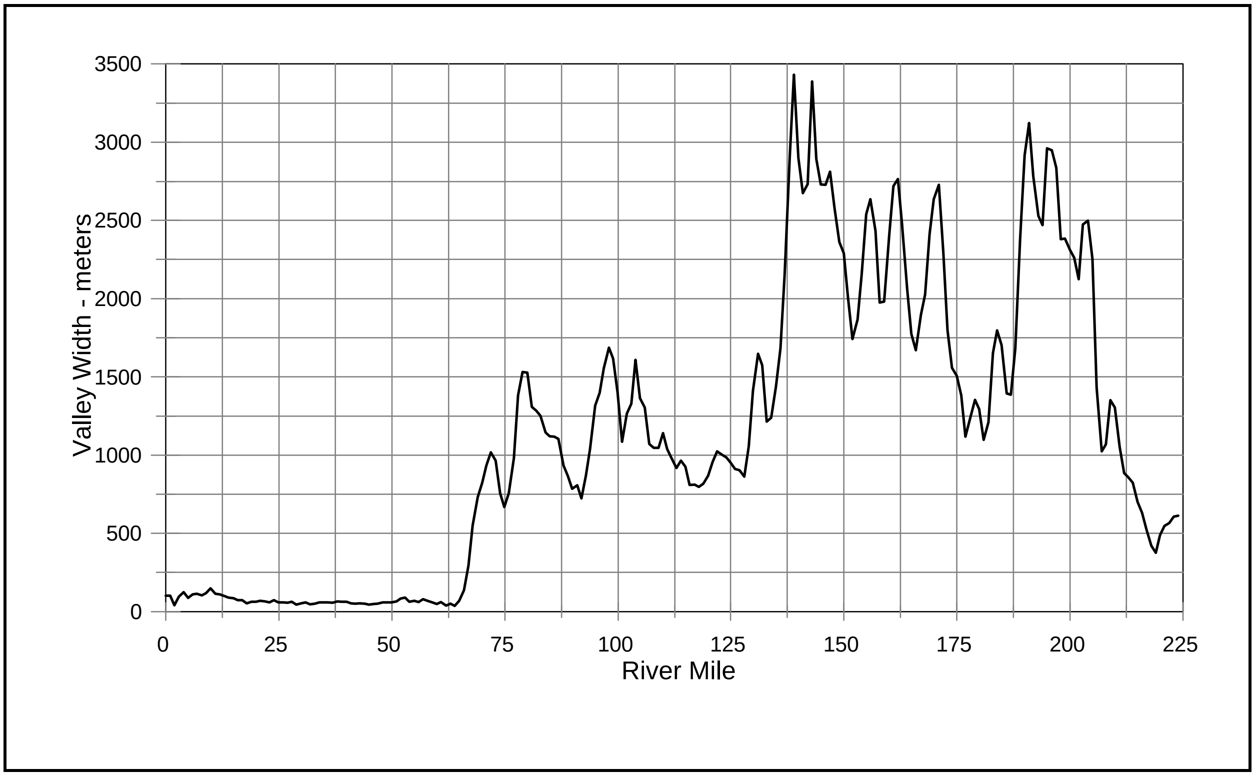

Figure 3.9. Valley Width by River Mile for the San Juan River

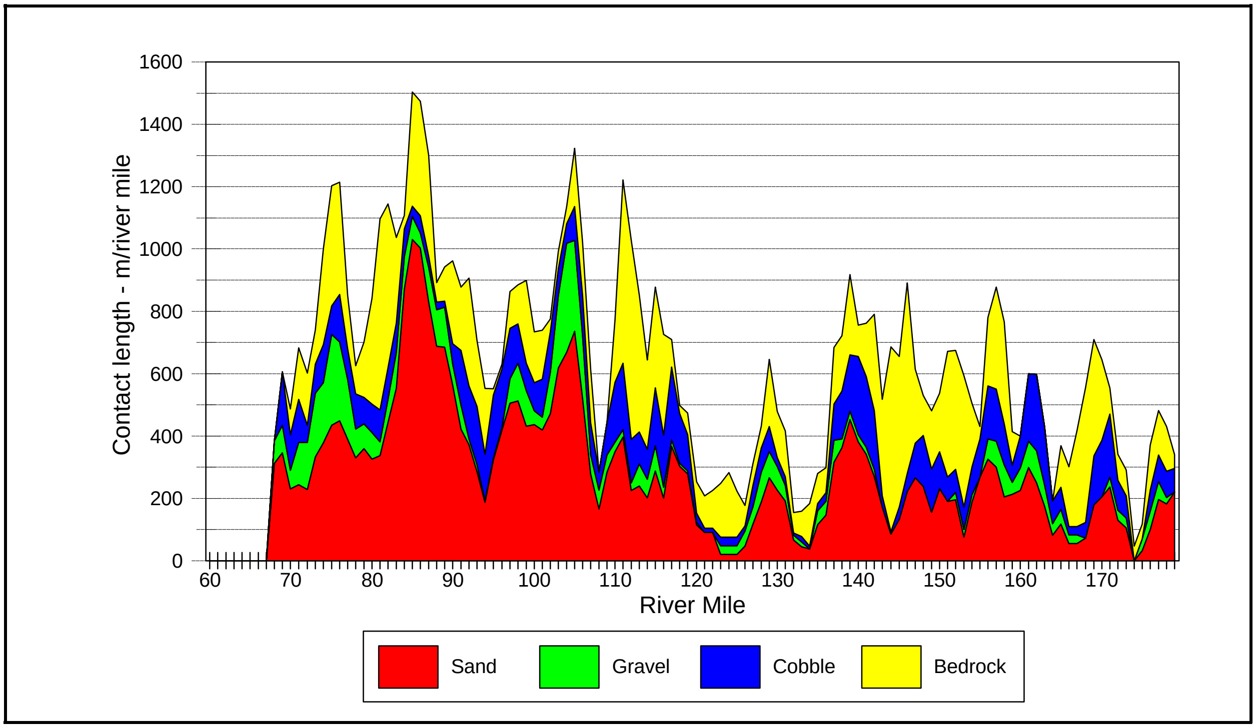

Figure 3.10. Three-Mile Running Average Channel Contact Geology (cutbank or bedrock) for the San Juan River.

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In general, the total cutbank length per mile increases with distance downstream from the Animas River confluence. The maximum lengths occur in an area that has been termed the "debris field" (RM 82 to RM 90) because of the large deposition of trees and brush in the channel. The channel is very active in terms of lateral movement in this reach, which is confirmed by the large amount of cutbanks.

Also the proportion of sand is high in this area, reflecting the heavy sand loading of the system in the downstream reaches.

The area of least cutbank activity occurs between RM 119 and RM 127. This is an area of relatively straight channels with an increase of bedrock and cobble control and some natural levee formation in the straight reaches which have stabilized the banks. The valley width is still over 1,000 meters in this reach so there is opportunity for lateral movement except for the naturally stabilized channel. A second area of channel stability occurs between RM 132 and RM 135. There are areas of active channel movement in this reach, but the low proportion of sand and relatively higher proportion of cobble in the area tends to stabilize the banks such that the channel change occurs more as overland flooding in the braided areas with subsequent cobble bar formations rather than cutbanks. Even though this area is braided, the main channel is relatively straight with more gradual bends and heavily vegetated banks that resist erosion.

The "mixer" lies midway between these two relatively stable reaches. It is characterized by moderate cutbank activity with a moderately high proportion of gravel. The active reaches above and below the two stable reaches on either side of the mixer show more cutbanks with much higher proportions of cobble and very little gravel.

It should be noted that cobble and gravel are plentiful throughout the reach mapped. Even in areas of low cutbank activity, there is abundant cobble. This high proportion of cobble and reduced sand content in the upper reaches of the river appear to have a stabilizing influence on the channel.

For the reach of river mapped (RM 68 to RM 179) sand predominated the cutbanks at 64%, with cobble constituting 22% and gravel 14%. While this is representative of the cutbank areas it may not reflect the distribution in the river banks as a whole. When examining trends, sand and gravel increase in proportion with distance downstream from the Animas confluence while cobble decreases. The proportion of cobble decreases from about 33% at the upper end to 17% at the lower end, while gravel increases from 8% to 16%. The proportion of sand increases from 59% to 66% from upstream to downstream. The trend is toward increasing cutbanks and decreasing bedrock control with distance downstream in this reach.

Riparian Vegetation

The distribution of the five main vegetation classifications (upland shrubs and herbaceous vegetation not included) is shown in Figure 3.11. Riparian vegetation density increases from the confluence of the Animas River downstream to about RM 130 and then declines rapidly between RM 130 and RM 110. Between RM 110 and RM 105, density again increases to about the level near

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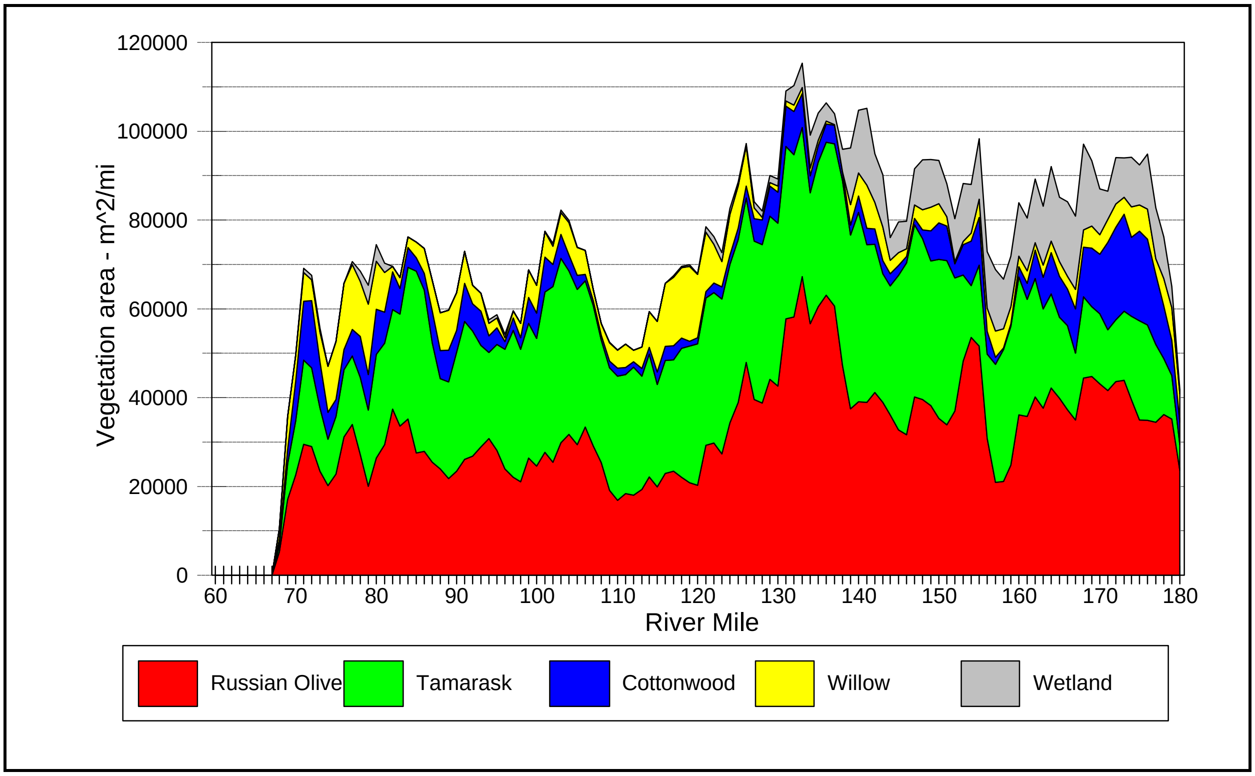

Figure 3.11. Main Channel Riparian Vegetation Area per River Mile for the San Juan River (3 mile running average).

Fruitland (RM 160) and remains relatively constant to the end of mapping at RM 68. Below RM 68 the riparian vegetation is sparse and not influential on channel morphology, since the canyon confines the channel.

Table 3.11 summarizes the relative abundance of each vegetation type mapped. Figure 3.12 shows the distribution of relative abundance for the five main types. Russian olive is the most abundant type, followed by tamarisk. Russian olive composition is relatively stable through the system with a few peaks and valleys but not much of a longitudinal trend. Tamarisk begins low, increases rapidly by about RM 160 and then is relatively constant until RM 115. Between RM 115 and RM 85 the relative abundance is at its highest level with a rapid decrease to the end, corresponding to an increase in willow. Cottonwood abundance is the highest at the two ends of the mapping range with the lowest values between about RM 100 and RM 165. Wetland plant abundance corresponds very closely to adjacent irrigation areas. Below RM 138 the wetland plant abundance is very low to non-existent. There is an increase in willow abundance between RM 112 and RM 125 that corresponds with a decrease in Russian olive and precedes an increase in tamarisk. As tamarisk increases, willow abundance decreases.

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Table 3.11. Relative abundance of vegetation by type.

	Relative Abundance - %		
Type	Average	Maximum (5 mile)	Minimum (5 mile)
Russian Olive	37	53	26
Tamarisk	30	49	10
Cottonwood	7	17	1
Willow	6	18	1
Wetland Herbaceous	5	18	0
Upland Herbaceous	6	26	1
Upland Shrub	9	19	0

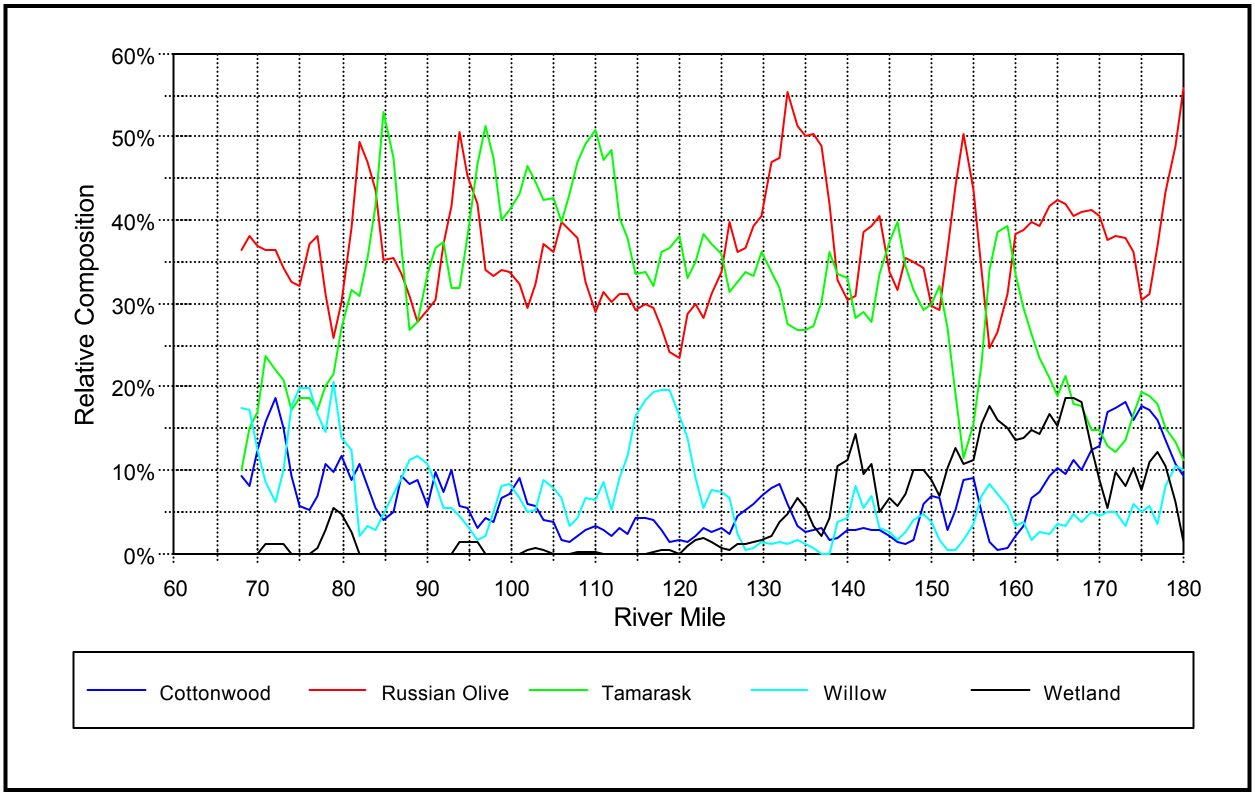

Figure 3.12. Relative Composition of Riparian Vegetation for the San Juan River (3 mile running average).

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Channel Gradient

The channel gradient by river mile is shown in Figure 3.13 presented as a 3-mile running average. The gradient is moderately flat for about 5 miles below Navajo Dam, steepening to its maximum gradient within about 18 miles of the dam. There is a general but small decrease in slope to about RM 140. Between RM 135 and RM 70 the river maintains a moderately flat gradient before it steepens in the canyon reach. The flattest reach of the river is between RM 0 and RM 14, where the slope averages about 0.05%. This flat slope is not natural, but is due to the backwater effect of Lake Powell, deposition of sediment and subsequent rerouting of the river over a higher sandstone bluff at RM 0. If the channel moves off the bluff, as it appears to be doing, the gradient will steepen, restoring itself to a gradient closer to that of the river in this reach before inundation by Lake Powell.

Channel Pattern

The 3-mile running average channel sinuosity is presented in Figure 3.14. The values shown are significantly different than those reported in 1992 due to the revised method of computation discussed under **METHODS**. Previously, the sinuosity was the highest in the canyon reach. Under the correctly calculated values for the conditions in the San Juan basin, the lowest sinuosity occurs in the canyon. The standard dividing point between straight and meandering channels occurs at a sinuosity of about 1.5 with the exception of two locations. The sinuosity is always below 1.5, so the river would not be classified as meandering.

Other Parameters

The categorical parameters dealing with tributary and man's influence on channel morphology are summarized in the following section. Aquatic habitat parameters utilized in reach definition analysis are also summarized in the next section.

Identify River Reaches

Utilizing the above referenced data sets, the eight reaches previously identified were verified and the boundaries between the reaches established. Table 3.12 presents the reach definitions and the mean value of each data set for each reach. Not all data sets were equally important in determining boundary divisions and testing for difference. The most significant variables (statistically, not geomorphologically) in descending order were: *valley width*, *adjacent irrigated lands*, *low-flow sandy area, sinuosity, high-flow island area, high-flow total water area, channel slope, low-flow riffle area* and *low-flow total water area*. This order of importance was determined from values of univariate F-tests. The mean values of the significant variables within the reaches that were utilized in the model are shaded in Table 3.12.

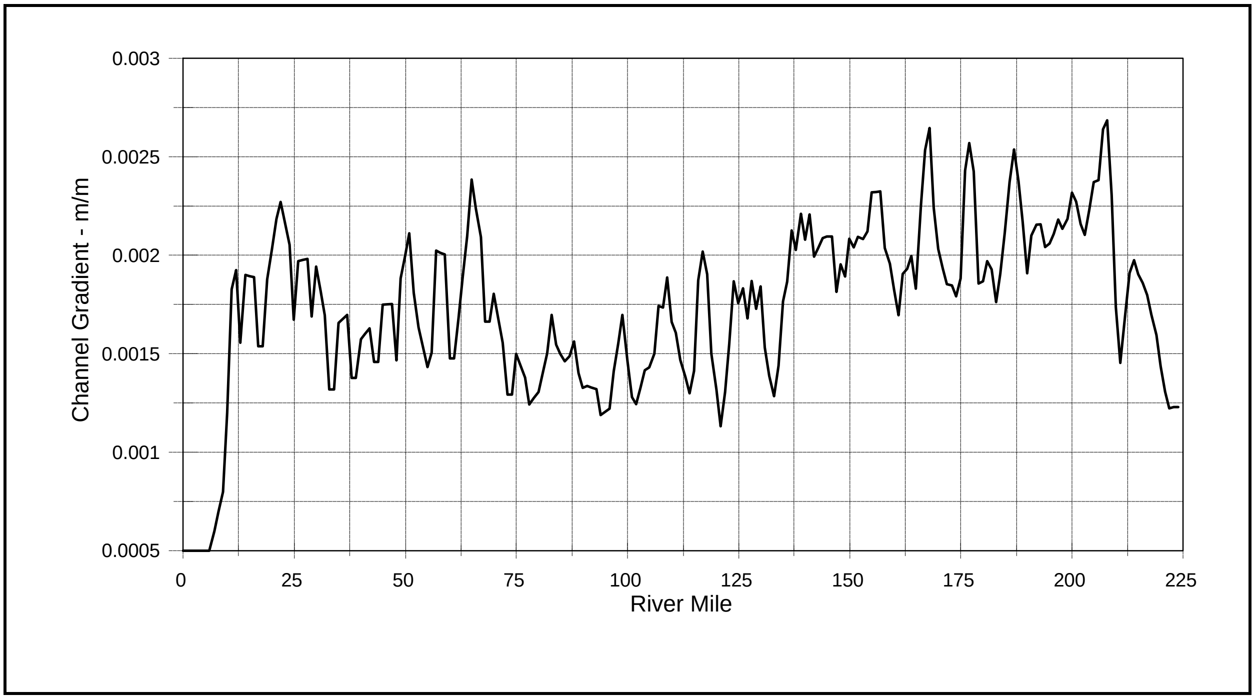

Figure 3.13. Three-Mile Running Average Channel Gradient for the San Juan River.

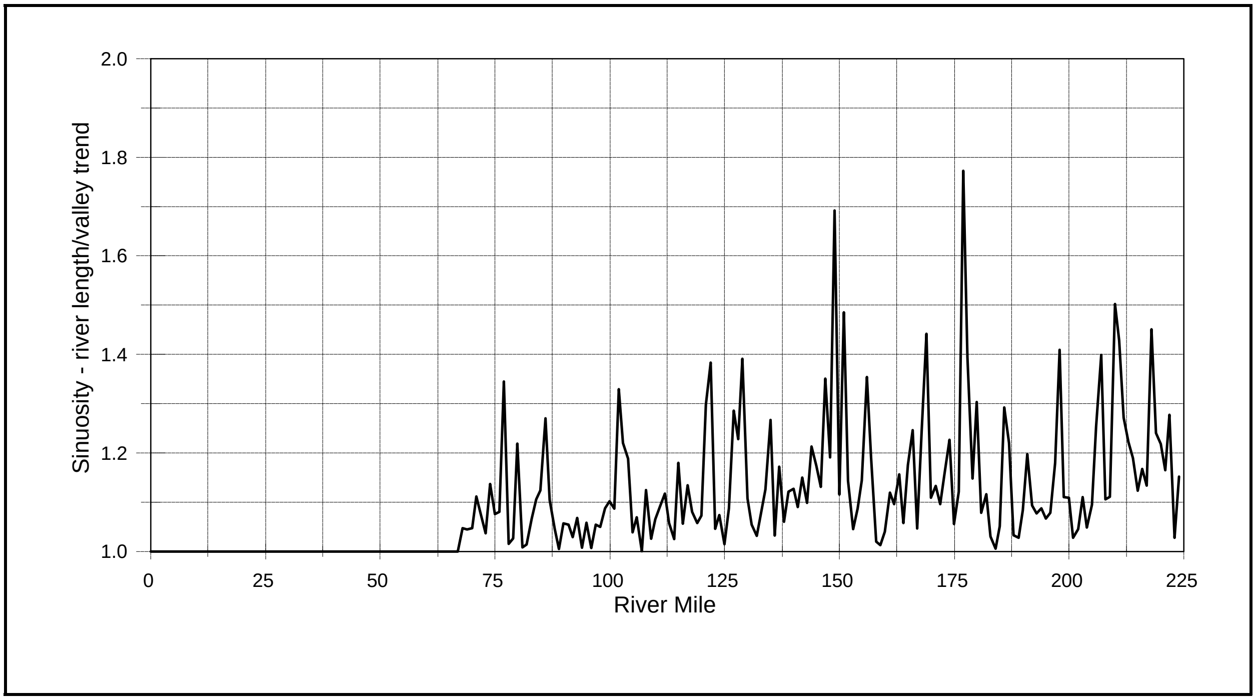

Figure 3.14. Three-Mile Running Average Channel Sinuosity for the San Juan River.

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Table 3.12. Reach definitions, variables considered and their mean values within reach utilized in delivering geomorphologically different reaches.

CATEGORY	REACH	1		2		3		4		5		6		7		8
	RIVER MILE	0-16		17-67		68-105		106-130		131-154		155-180		181-213		214-224
HABITAT - m^2/mi																
High Flow	Total Water Surface	152,314	≠	97,161	≠	199,049	≠	171,983	≠	206,925	≠	133,983	≠	102,519		150,883
	Low Velocity Types	1,920		2,015		1,481		1,893		1,861	≠	946		1,241		13,642
	Riffles/Chutes	42	≠	27,697		30,139		31,237		43,041	≠	10,816	≠	3,713	≠	13,050
	Sand Type	5,704	≠	363	≠	15,132	≠	2,794		3,224	≠	760		1,615		3,370
	Cobble Type	0		43	≠	3,726	≠	1,208		1,471	≠	632		364	≠	1,692
	Islands 3 mi average	0		109	≠	84,708	≠	117,354	≠	266,896	≠	58,403		52,958		53,469
Intermediate Flow	Total Water Surface	136,072	≠	74,415	≠	123,940		119,980		122,787						
	Low Velocity Types	4,646		1,192	≠	2,136		2,256		2,546						
	Riffles/Chutes	3,827	≠	19,013		14,373	≠	25,268	≠	38,382						
	Sand Type	43,108	≠	1,962	≠	8,932		6,923		3,392						
	Cobble Type	1,011		2,342	≠	7,139		7,785	≠	3,655						
	Islands 3 mi average	200		320	≠	51,940	≠	82,210	≠	188,055						
Low Flow	Total Water Surface	114,291	≠	72,142	≠	113,314	≠	104,522		107,422	≠	92,933	≠	77,043		94,636
	Low Velocity Types	2,239	≠	890	≠	1,897		2,026	≠	4,328	≠	8,929	≠	732	≠	17,921
	Riffles/Chutes	9	≠	16,865		14,683		16,113	≠	26,164		26,641	≠	6,746	≠	30,260
	Sand Type	26,112	≠	1,125	≠	7,195		5,526	≠	2,918	≠	586		1,337		0
	Cobble Type	309	≠	1,522	≠	2,572	≠	4,036		3,197		2,584		3,185		2,988
	Islands 3 mi average	0		173	≠	44,473	≠	71,249	≠	196,178	≠	21,675	≠	46,921		60,728
RIPARIAN VEGETATION - m^2/mi																
	Cottonwood					6,094	≠	2,847		4,909	≠	10,043				
	Russian Olive					26,643		28,701	≠	46,053	≠	35,119				
	Tamarisk					25,167	≠	31,224		32,536	≠	19,124				
	Willow					6,592		7,393	≠	3,007		4,499				
	Upland Herbaceous					1,811		7,182	≠	15,801	≠	9,569				
	Upland Shrub					7,897	≠	7,056	≠	2,349		2,647				
	Wetland Herbaceous					524		718	≠	8,737		11,509				

Note that shaded rows show significant variables

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Table 3.12. (Continued)

CATEGORY	REACH	1		2		3		4		5		6		7		8
	RIVER MILE	0-16		17-67		68-105		106-130		131-154		155-180		181-213		214-224
CHANNEL - 3 mile average																
	Valley Width - m	102	≠	66	≠	1122	≠	986	≠	2299		2028		1957	≠	574
	Channel Slope - ft/ft	0.00105	≠	0.00178	≠	0.00143	≠	0.00164	≠	0.00193	≠	0.00209		0.00213	≠	0.00160
	Sinuosity	1.00000		1.00001	≠	1.09096	≠	1.12311	≠	1.16862		1.18715		1.15081	≠	1.19527
STREAM CHANNEL																
	Bedrock - m/mi					206		182		243		140				
	Total Cutbank					713	≠	324		323		316				
	Contains Sand					93.6%	≠	96.4%		86.2%		84.6%				
	Contains Gravel					29.7%	≠	31.1%	≠	7.8%	≠	26.5%				
	Contains Cobble					34.6%		64.0%		62.2%		58.1%				
	Sand Only					86.1%	≠	66.4%		68.7%		41.0%				
	Gravel Only					21.3%	≠	9.3%		6.2%		10.8%				
	Cobble only					15.2%		21.7%		23.2%		25.3%				
CATEGORICAL VARIABLES																
	Adjacent Irrigated Area - %	0.0%		0.0%		23.7%		0.0%		83.3%		100.0%		100.0%		30.0%
	Major Tributary - Ephemeral	0		0		6		3		2		0		2		2
	Major Tributary - Perennial	0		0		2		1		1		3		1		0
	Bridge	0		1		4		1		1		2		2		1
	Diversion	0		0		0		0		1		4		1		1
	Oil Well	0		2		4		0		0		0		0		0
	Pipe Crossing	0		0		1		0		2		1		0		0
	Borrow Pit	0		1		1		0		0		0		0		5
	Pond	0		1		6		2		2		0		0		0
	Road	2		1		6		0		0		0		0		0
	Sewage Treatment	0		0		3		0		3		3		0		0
Note that shaded rows show significant variables																

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Based on the results of discriminant analysis, a table of predicted versus assigned reach numbers was generated. The reaches at the boundaries were reassigned to the neighboring reach. The analysis was repeated to verify that the assigned boundaries between reaches matched those predicted by the model.

The final reach boundaries are shown in row 2 of Table 3.12. The final frequency assignment of river miles within reaches is shown in Table 3.13.

As seen from Table 3.13, the discriminant function found from the analysis predicts Reaches 1 and 8 perfectly, Reaches 2 and 6 with one out-of-place river mile, Reaches 4 and 7 with two out-of-place river miles and Reaches 3 and 5 with five out-of-place river miles. Reaches 3, 4, 5, 6 and 7 are the least distinct of the reaches and show the most overlap. In spite of this ambiguity, the reach assignments are very good (Pearson chi-squared test statistic = 1332.356 with probability = 0.000 that there is no relationship between the assigned and the predicted reaches). The predicted reach assignments may become better if the vegetation and channel-contact surveys are extended to the whole length of the river. The out-of-place river miles come not from the boundaries, but from inside the reaches. For this reason the boundaries of the reach assignments, shown in row 2 of Table 3.12, are the best statistical estimates.

Table 3.13. Frequency two-way table categorized by assigned and predicted reaches.

Assigned Reaches	Predicted Reaches							
	1	2	3	4	5	6	7	8
1	**17**	0	0	0	0	0	0	0
2	0	**50**	0	0	0	0	0	**1**
3	**1**	0	**33**	**4**	0	0	0	0
4	0	0	**2**	**23**	0	0	0	0
5	0	0	0	**1**	**19**	**3**	**1**	0
6	0	0	0	0	0	**25**	**1**	0
7	0	0	0	0	**1**	**1**	**31**	0
8	0	0	0	0	0	0	0	**11**

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The difference in reaches can be illustrated by plotting some significant variables (standardized to plot on same scales) versus river mile. Figure 3.15 is a plot of *valley width, adjacent irrigated lands, low-flow sandy area, sinuosity,* and *high-flow island area*. Note how the variables shift in values between reaches. Not only do the mean values shift up or down, but the vertical spread or variances are different between reaches. These dissimilarities in the San Juan River imply that (1) the characteristics of proposed reaches are different and (2) the chosen variables are useful in defining separate habitat reaches.

Between the reach columns in Table 3.12 is the unequal symbol, ≠, denoting the values bracketed on the left and on the right are significantly different at the 95% or greater confidence level. The two-sample *t*-test was used to compare the means of the two groups of variables between each pair or reaches. For the variable, *high-flow total water area*, the mean values were all different between neighboring reaches except Reaches 7 and 8. For the variable, *high-flow low velocity type*, the mean values were all the same between neighboring reaches except Reaches 5 and 6 which were significantly different. Changes in the mean values which are different between reaches would be of special interest in monitoring changes along the river during the study.

River Geometry Analysis

Cross Section Measurement for RT Series Transects

Figure 3.16 shows the mean bed elevation for each of the RT series transects from March 1992 through August 1998. The March 1992 survey was used as the baseline and the relative elevation of each transect was set to 1.0 meter. If there has been net deposition since March 1992 the relative bed elevation will be greater than 1.0 meter. Conversely, if the elevation is less than 1.0 meter, scour has occurred. Due to a survey error in March 1992, RT-07 has no data point for the first survey. The relative elevation in July 1992 for this transect was set at the mean of the other transects to allow comparison from July 1992 on.

Table 3.14 summarizes the response of each transect. While the transects were selected to represent similar conditions in the river some variation in sites is unavoidable. The position of the transect relative to channel splits, the gradient at the location of the transect, the alignment of the channel (e.g. on a bend, straight, etc.) and the substrate conditions vary somewhat among the transects and influence the channel response.

Figure 3.17 shows the mean bed elevation as an average of all RT transects (RT-08 excluded). On average, the pre-runoff surveys show a greater mean bed elevation than the post-runoff surveys. The average pre-runoff mean bed elevation has dropped in each of the study years through 1996. The post-runoff mean elevation also decreased in each study year through 1995, with increases from the previous year in 1996 and 1998.

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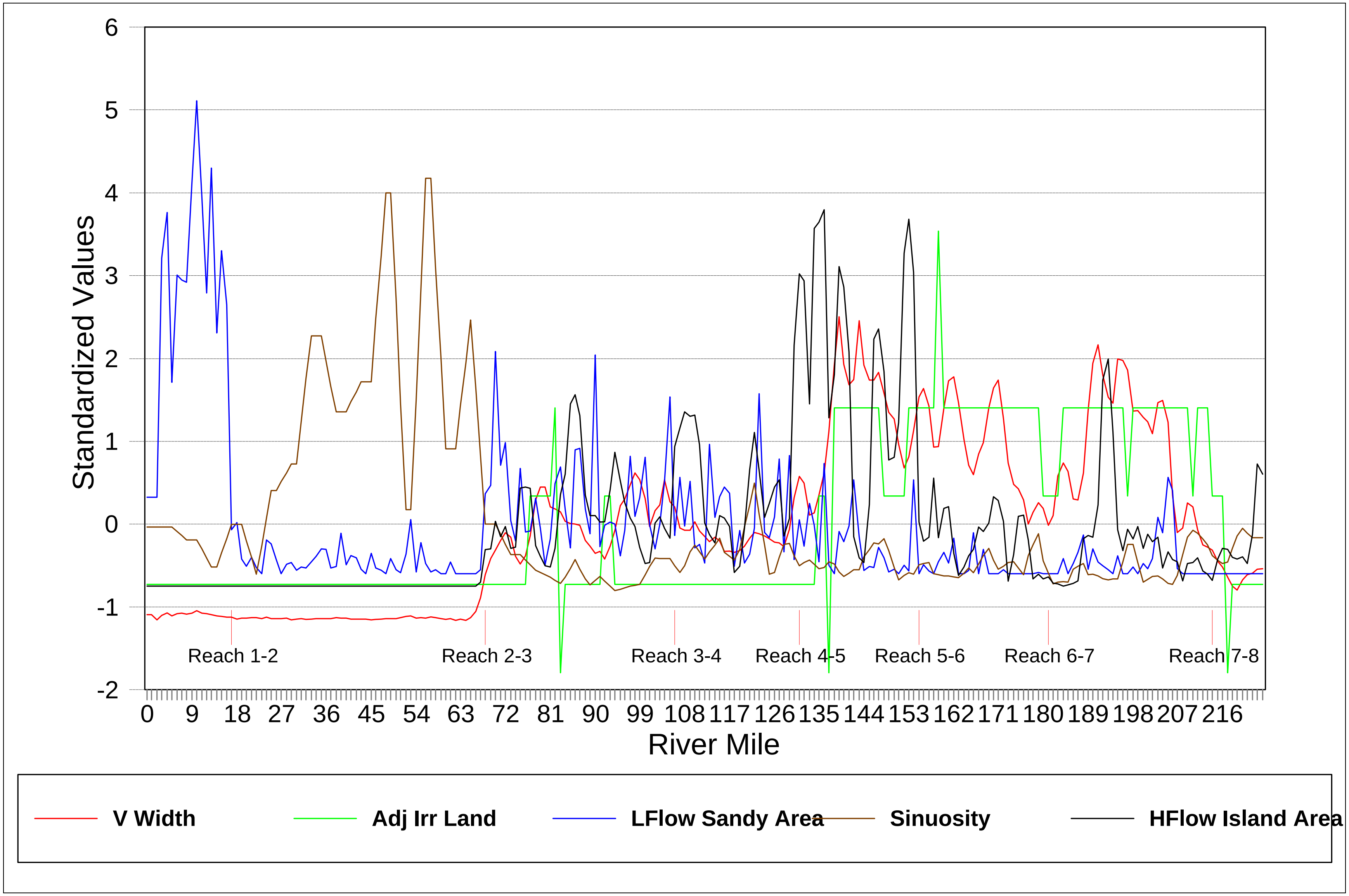

Figure 3.15. Distribution of Normalized Key Parameters used in Reach Definition.

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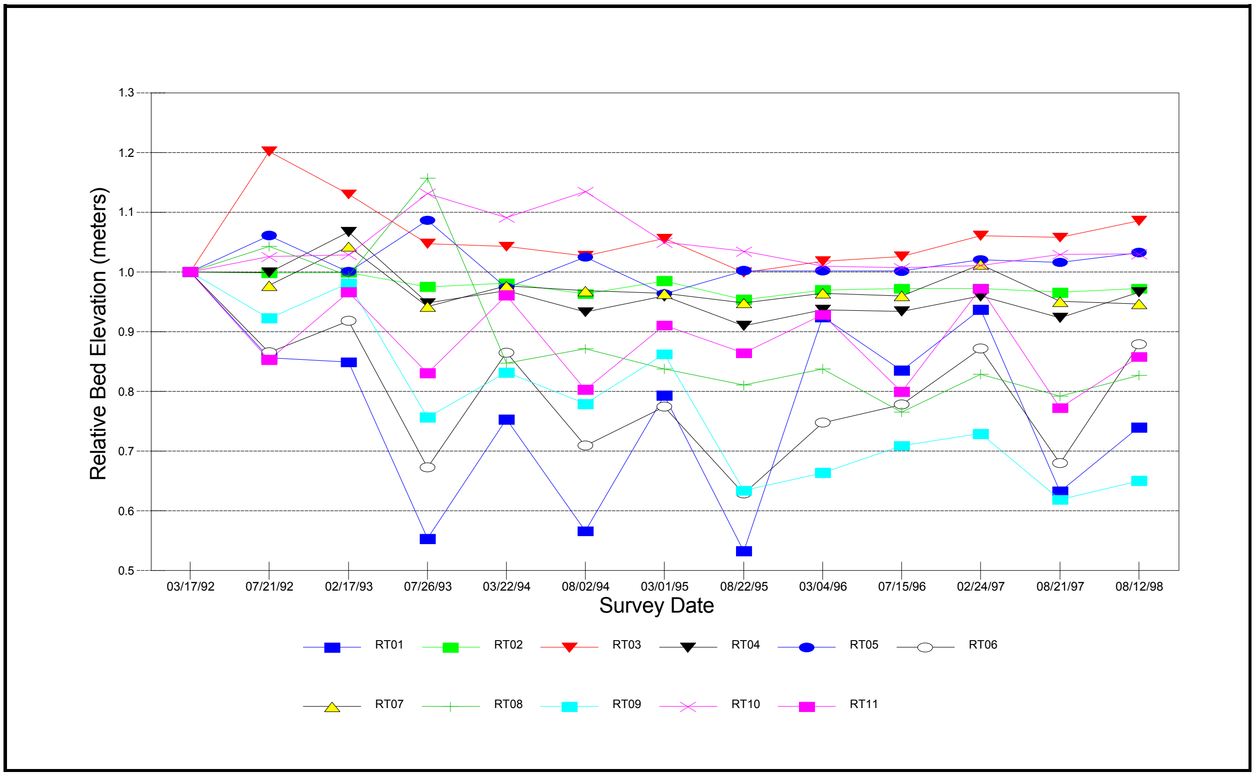

Figure 3.16. 1992-1998 Relative bed elevation for each of the RT transects on the San Juan River.

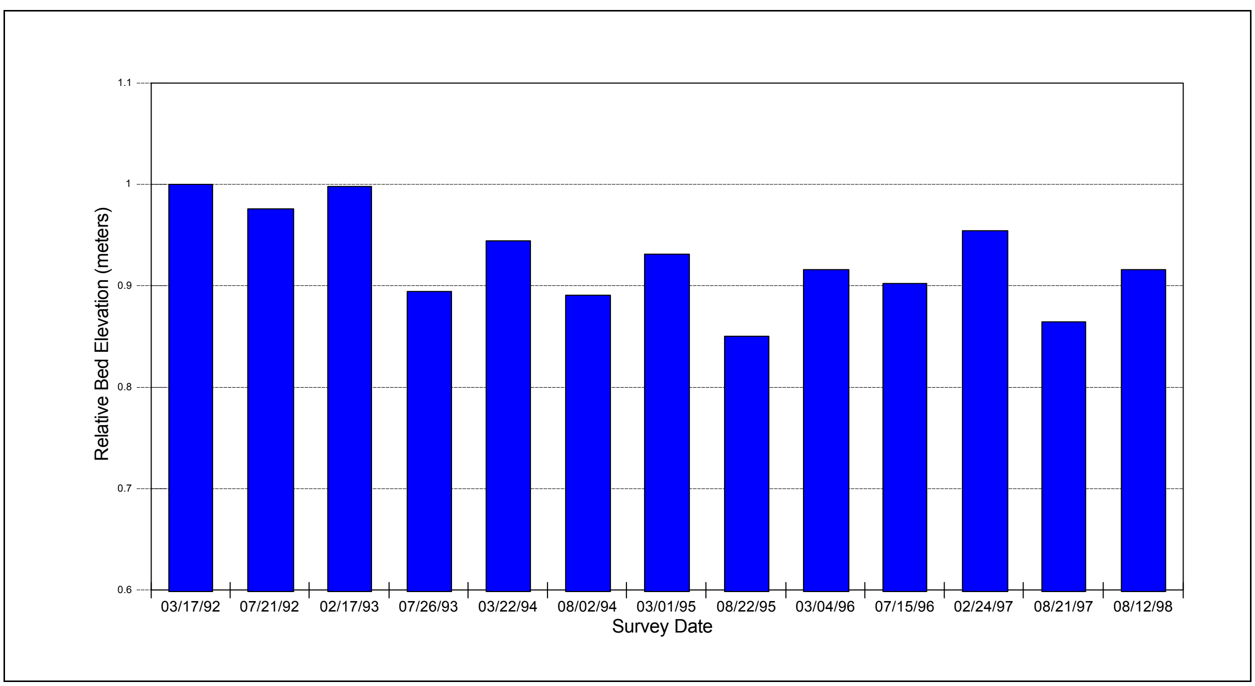

Figure 3.17. 1992 - 1998 Average relative bed elevation for RT series transects, on the San Juan.

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Table 3.14. Summary of RT-series transect changes with time.

Transect	Net Change- m 1992-1998	Description of the Pattern of Change
RT-01	-0.26	Rapid scour to 1993, dynamic di-annual change, reached minimum elevation in 1995
RT-02	-.03	Gradual scour, little di-annual change, minimum in 1995
RT-03	.09	Initial deposition, subsequent scour, minimum in 1995, gradually increasing since
RT-04	-.03	Initial deposition, rapid scour in 1993, stable since with some diannual variation, minimum in 1995
RT-05	.03	Typically deposits during runoff and scours at low flow, minimum before runoff in 1995, gradually increasing since
RT-06	-.12	Substantial initial scour, minimum in 1995, large diannual variation
RT-07	-.05	Relatively stable with small diannual variation. Minimum in 1993 and 1998.
RT-08	-.17	Relatively stable except for the loss of an irrigation reservoir on the right bank in 1993 that caused large scour. Minimum in 1996.
RT-09	-.35	Large scour in 1993 and 1995. Minimum in 1997
RT-10	.03	Deposited until 1995, minimum in 1996. Relatively stable, largest scour (1995) was between runoff events
RT-11	-.14	Strong diannual pattern, minimum in 1997
MEAN	-.09	Diannual pattern with minimum in 1995
MEAN w/o RT-08	-.05	RT-08 scour is artificial due to reservoir embankment failure. Not included in analysis

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Using the 1992 through 1997 data (1998 could not be used since there was no spring sample), mean elevation change during runoff was correlated to runoff volume at Four Corners, peak discharge at Four Corners and prior deposition (accumulated deposition since the previous low elevation). Discharge and elevation change data used in the analysis appear in Table 3.15. The results of the regression analyses appear in Table 3.16 for the individual transects and the average of all transects.

The best regression model for the average of all transects correlates the change in mean bed elevation during runoff to the March through July runoff and the previous non-runoff deposition. In years when runoff did not scour to the previous year's level, the accumulated deposition was used. When averaging the scour and deposition for 10 transects (RT-08 was removed from the analysis due to the failure of a reservoir bank on the right abutment), runoff scour was linearly correlated to runoff volume and previous deposition ($R^2 = 0.95$, $n = 5$, $p = .05$). Averaging the response across transects removes much of the random variability among transects. The resulting regression relationship well represents the average change, but will not predict the change at any given cross-section.

A second regression analysis was performed utilizing all the transect data, rather than averaging the response of the transects. With 50 data points, the regression is significant, but only explains a little over half of the variability seen when using the model used for the average condition(see Table 3.16 for regression results). The correlation is improved to explain about 62% of the variability when the % cobble before runoff and the % cobble after runoff are added to the model. The predicted changes in mean cross-section elevation using these models are plotted in Figure 3.18 plotted against the measured change for each of the surveys at each transect. The same trend of increasing scour with increasing flow and increasing previous year deposition is shown. The resulting scour appears to be influenced by the amount of cobble present before and after runoff. Sour decreases with increased cobble before runoff and increases with increasing cobble after runoff.

Table 3.15. Discharge at Four Corners and elevation change data for RT cross-sections.

Year	Annual Total (Acre Feet)	Mar-Jul Total (Acre Feet)	Apr-Jun Max (cfs)	Scour During Runoff (m)	Deposition Between Runoff (m)	Cumulative. Deposition Between Runoff[1] (m)
1991	1,084,775	573,863	5,160			
1992	1,510,148	1,074,795	8,900	-0.024		
1993	2,212,941	1,714,328	10,300	-0.104	0.022	0.022
1994	1,446,358	1,039,601	10,000	-0.054	0.050	0.050
1995	2,098,551	1,624,927	12,100	-0.081	0.041	0.041
1996	814,368	431,913	3,540	-0.014	0.066	0.066
1997	1,880,723	1,319,155	11,900	-0.091	0.052	0.104

[1] Includes previous year's deposition remaining after scour in years when scour is less than deposition.

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Table 3.16 Results of regression analysis of channel change (scour or deposition) during runoff at RT cross-sections vs runoff and change during previous non-runoff period.

Transect	R^2	n	p	Intercept	Flow Coeff.	Previous Change Coeff.
average - scour = $f_{\text{peak cfs}}$	0.62	6	0.06	.026	-9.19E-06	
average - scour = $f_{\text{runoff af}}$	0.78	6	0.02	.022	-6.94E-08	
average - scour = $f_{\text{runoff af \& deposition}}$	0.95	5	0.05	.033	-7.13E-08	-0.257
all - scour = $f_{\text{runoff af \& deposition}}$	0.53	50	<.01	.069	-8.07E-08	-0.642
all - scour = $f_{\text{runoff, deposition, \% cobble before runoff and \% cobble after runoff}}$	0.62	50	<.01	.0074	-5.73E-08 .0017 (% cobble before)	-.4192 -.001 (% cobble after)
following expressed as scour = $f_{\text{runoff af \& deposition}}$						
RT-01	.90	5	.10	.050	-1.93E-08	-0.167
RT-02	.72	5	.28	.010	-2.19E-08	0.110
RT-03	.92	5	.08	.030	-5.11E-08	0.369
RT-04	.82	5	.18	.047	-4.50E-08	-1.044
RT-05	.75	5	.25	-.024	3.12E-08	-0.455
RT-06	.85	5	.15	0.145	-1.92E-07	-0.363
RT-07	.85	5	.15	0.039	-1.56E-08	-1.447
RT-09	.97	5	.03	0.164	-2.09E-07	-0.366
RT-10	.58	5	.42	0.003	4.09E-08	0.809
RT-11	.69	5	.31	0.084	1.047E-08	-1.772
Reach 6 - average	.94	5	.06	.023	-1.04E-07	-0.129
Reach 5 - average	.78	5	.22	.020	-2.86E-08	-0.018
Reach 4 - average	.82	5	.18	.095	-1.18E-07	-0.4417
Reach 3 - average	.85	5	.15	.012	-4.96E-08	-0.458

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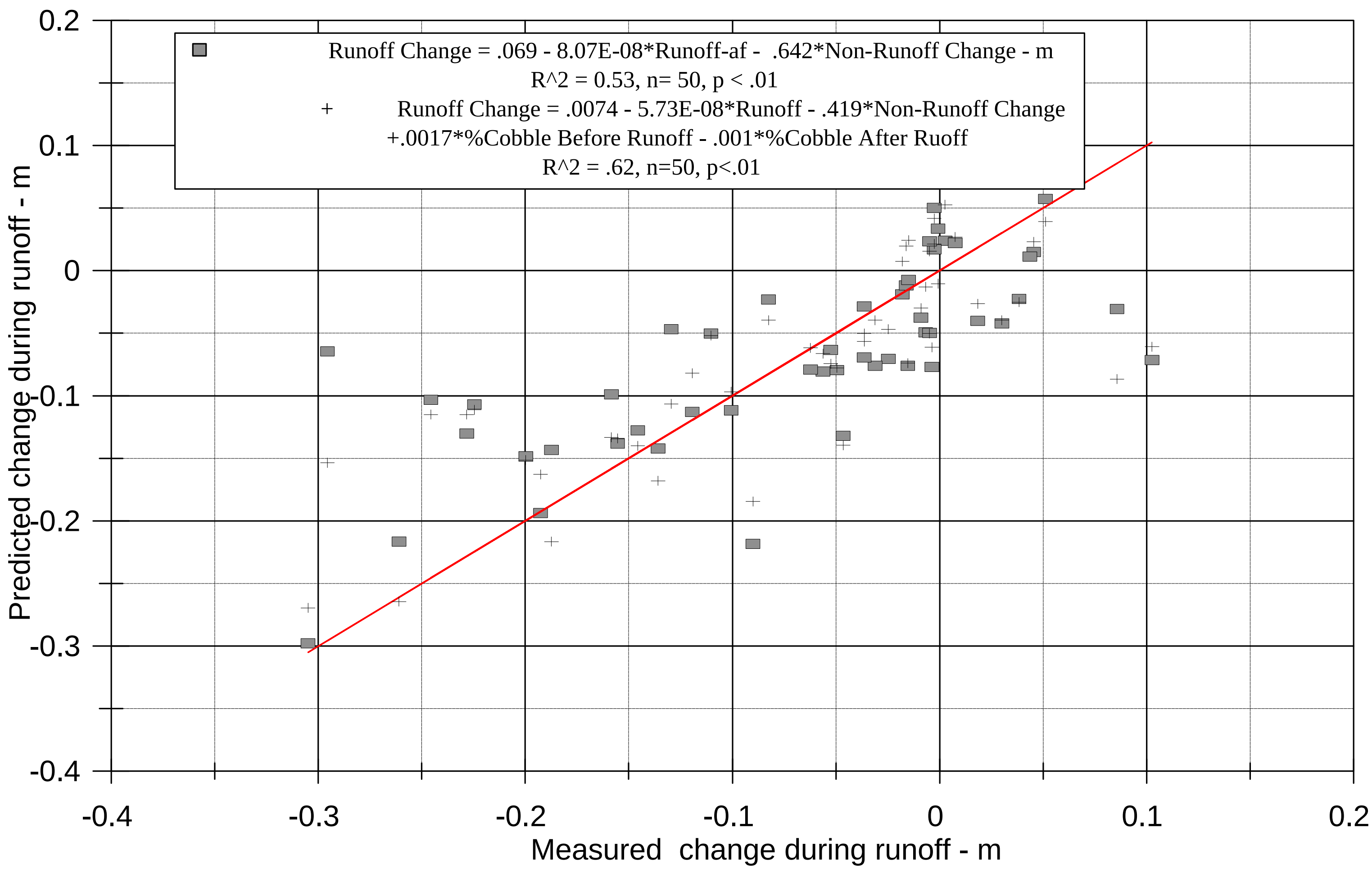

Figure 3.18. Predicted vs measured channel change in response to runoff for all RT transects in the San Juan River (1993-1997).

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The resulting regression models for both the averaged data and the full data set show the same trend of increasing scour with increasing flow volume and increasing previous year deposition. In both models, deposition can occur when the flows are below a certain level, although the predicted thresholds are different.

Table 3.16 also shows the regression results for each individual cross-section. In this case, only one relationship is significant at the 95% level and three at the 90% level. The models vary depending on the response of the cross-sections, with two (RT-5 and RT-10) showing increased scour with decreased flow (deposition during runoff, scour during non-runoff).

Also shown in Table 3.16 are the regression results for data averaged by reach. In this case, RT-02 is averaged with RT-01 for Reach 6, even though RT-02 is actually 1 mile into Reach 5. Although the R^2 values are better, in general, than the single transect regressions, none are significant at the 95% level and only one at the 90% level. The models in each case do suggest increasing scour with increased flow and previous deposition, similar to the average of all transects.

The natural variability in transects is obvious in the examination of Tables 3.14 and 3.16 and Figure 3.16. Careful examination of the actual response of the cross-sections with consideration of their position in the river explains most of this variability. For example, RT-05 is located downstream of a sharp channel bend to the right and accumulates sediment during high flow conditions in the lee of the point bar. At low flow this material is eroded. RT-10 is positioned such that the right side of the transect is just downstream of a diagonal cobble bar that proceeds downstream to form a mid-channel island below the transect. At high flow the drop over the bar is submerged and material deposits behind the bar. At low flow the gradient steepens in this location and the deposited material erodes.

The portion of cobble substrate for these cross-sections is highly variable but has increased during the research period, both before and after runoff. Table 3.17 presents the cobble percentages during each survey for the RT cross-sections. The cobble portion of the substrate at the RT cross-sections reached their peak following runoff in 1993. This was the year of highest volume runoff and the lowest sediment load. 1995 had nearly the same volume, but the sediment load was higher due to some storm influence. 1997 and 1998 were both heavily storm influenced on the descending limb of the hydrograph, resulting in more fine sediment. Typically low flow years like 1996 and 1998 have the least cobble substrate after runoff, although this can be effected by storm inflow prior to survey as occurred in 1997 and 1998.

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Table 3.17. Percent cobble substrate for the RT series transects on the San Juan River (1992-1998).

	Survey Date												
Transect	03/17/92	07/21/92	02/17/93	07/26/93	03/04/94	08/02/94	03/01/95	08/22/95	03/04/96	07/15/96	02/24/97	08/21/97	08/12/98
RT01	0%	26%	22%	100%	5%	85%	7%	87%	13%	24%	0%	30%	36%
RT02	50%	54%	86%	100%	87%	85%	84%	87%	85%	68%	88%	86%	72%
RT03	33%	47%	65%	87%	80%	66%	62%	73%	69%	65%	55%	60%	60%
RT04	35%	35%	75%	88%	59%	87%	65%	90%	77%	80%	63%	74%	65%
RT05	16%	0%	30%	70%	66%	67%	62%	70%	42%	63%	55%	67%	60%
RT06	19%	0%	24%	43%	13%	23%	16%	38%	32%	26%	18%	23%	20%
RT07		69%	61%	80%	69%	80%	66%	90%	78%	92%	72%	88%	79%
RT08	26%	46%	57%	20%	16%	11%	14%	13%	17%	22%	13%	25%	13%
RT09	38%	38%	46%	73%	35%	50%	35%	44%	58%	46%	34%	33%	19%
RT10	50%	78%	65%	79%	88%	35%	77%	57%	73%	75%	61%	60%	72%
RT11	3%	13%	11%	47%	11%	43%	3%	13%	14%	59%	8%	23%	25%
Average	27%	37%	49%	72%	48%	58%	45%	60%	51%	56%	42%	52%	47%

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Cross Section Measurement for Mixer Transects

Figure 3.19 shows the mean bed elevation for each of the mixer series transects from February 1993 through July 1998. Transects 1-4 were first surveyed in February 1993. Transects 5-8 were first surveyed in September 1993. All data were normalized to use the July/September 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.20 shows the average relative bed elevation for M-3 through M-8 transects. M-1 and M-2 were not included in the average. M-1 experienced a channel course change in 1993. A new main channel was formed in a location of a small secondary channel, subsequently filling the old main channel. M-2 was the location of the formation of the new main channel, requiring a change in the width of the survey. It filled on the left and scoured on the right, without a lot of net change. However, after the change, the cross-section ran diagonally across the new channel and became impossible to survey at high flows. It is not included in the average due to the loss of these data points.

Table 3.18 summarizes the response of each transect. These transects are more variable in nature than the RT series and tend to represent more dynamic locations. They were also surveyed more frequently to better determine the response to the ascending and descending limbs of the hydrograph. The general trend during most runoff periods is to exhibit scour on the ascending limb and deposition on the descending limb. In all years except 1997, scour is greater during the non-runoff period than during runoff. The dynamics at these locations are much different than at the RT cross-sections. The gradient is typically higher and they are located in areas of significant cobble movement and channel change. The extreme example is RT-01 with over 1.0 m of fill as the channel was isolated during one runoff event.

Most of these cross-sections have exhibited a pattern of scour since mimicry of the natural hydrograph was initiated in 1992, similar to the RT cross-sections and greater in magnitude. Further, the pattern of stability that is seen in the RT surveys is not apparent, with 1997 being the lowest year to date and the 1998 survey shows an average elevation below the earlier years. Stability is not yet evident. However, this is a historically dynamic area and these locations have historically changed more than other areas of the river. The lack of stability in six years of data is not alarming.

Table 3.19 presents the cobble percentages during each survey for the mixer series cross-sections. Cobble percentages are generally higher and less variable for these surveys than for the RT series. There is no statistically significant difference in the average cobble percentages with time.

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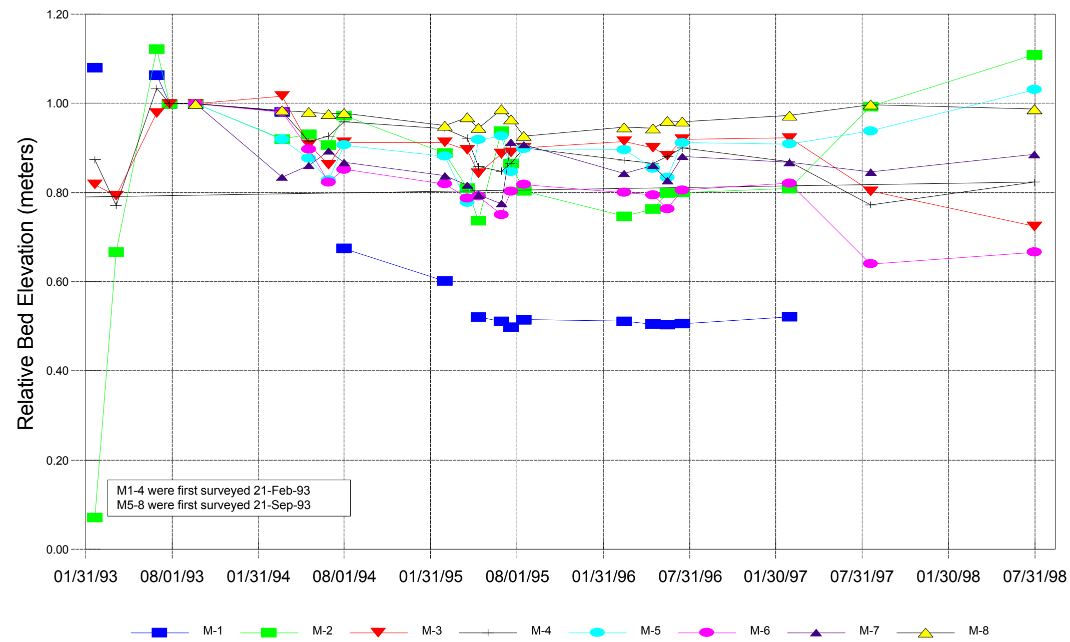

Figure 3.19. Relative bed elevation for all Mixer series transects on the San Juan River (1993-1998).

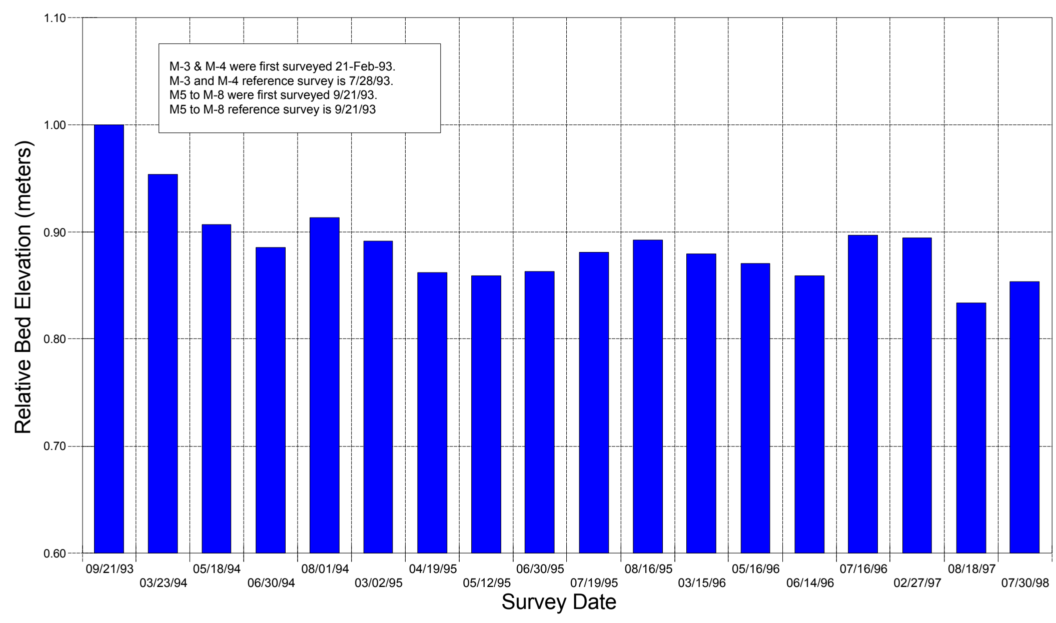

Figure 3.20. Average relative bed elevation for Mixer series transects (M-3 to M-8) on the San Juan River (1993-1998).

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Table 3.18. Summary of Mixer series transect changes with time.

Transect	Net Change- m 9/83-8/98	Description of the Pattern of Change
M-01	-0.48	First survey in Feb 93. Total change -0.55 m. Could not survey at high flow, so several missing survey points. Heavy scour in '94 as secondary channel enlarged. Some scour in '95. Stable since. No re-filling between runoff.
M-02	0.11	First survey in Feb 93. 1.04 m total change. Heavy fill in 1993 as this channel was isolated and new channel developed on the right sight of M-01. Stable from '95-97. Filled in '97 and '98. Isolated at low flow.
M-03	-0.28	First survey in Feb 93. -0.09 m total change. Some fill in 1993, scour in '94, stable until '97, scour in '97 and '98.
M-04	-0.18	First survey in Feb 93. -0.05. Filled in '93 and '98. Scoured in '94, '95 and '97.
M-05	0.03	Scoured in '94, scoured and re-filled in '95 and '96, filled in '97 and '98.
M-06	-0.33	Scoured in '94 and '97, scoured and re-filled in '95 and '96, stable in '98
M-07	-0.11	Scoured before runoff in '94, scoured and re-filled in '95 and '96, stable since.
M-08	-0.01	Very stable with some scour in '95 and gradual re-fill since.
MEAN	-0.22	General pattern of scour at peak runoff and refill on descending limb. Greatest net scour in 1994 and 1997. Tend to be erosional between runoff and depositional during runoff, except for 1997.
MEAN w/o M-1&2	-0.15	M-1 is missing several surveys. M-2 filled heavily in 1993 as a new secondary formed north of the transect, isolating it except at high flow.

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Table 3.19. Percent cobble substrate for the Mixer series transects on the San Juan River (1993-1998).

Date	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6	Mixer 7	Mixer 8	Average M-3 to M-8
02/21/93	83%	74%	29%	46%					
04/06/93		0%	39%						
06/30/93	94%	23%	73%	90%					
07/28/93	96%	51%	80%	71%					
09/21/93					63%	44%	37%	60%	59%*
03/24/94	83%	26%	70%	69%	49%	29%	34%	54%	51%
05/18/94		28%	75%	89%	26%	36%	41%	49%	53%
06/30/94		36%	75%	64%	43%	23%	39%	64%	51%
08/01/94	89%	37%	73%	70%	51%	17%	39%	65%	52%
03/02/95	87%	27%	62%	65%	52%	33%	37%	66%	53%
04/19/95		32%	65%	74%	54%	39%		67%	50%
05/12/95	75%	68%	74%	68%	52%	37%	52%	61%	57%
06/03/95	83%	29%	82%	66%	51%	46%	59%	64%	61%
07/19/95	92%	34%	79%	73%	57%	38%	41%	68%	59%
08/16/95	93%	35%	82%	75%	51%	36%	43%	41%	55%
03/06/96	94%	32%	75%	73%	61%	39%	46%	66%	60%
05/24/96	93%	46%	73%	76%	54%	50%	44%	66%	60%
06/14/96	94%	34%	75%	75%	53%	46%	40%	58%	58%
07/16/96	91%	50%	80%	69%	54%	36%	44%	64%	58%
02/27/97	87%	27%	72%	75%	48%	38%	43%	51%	55%
08/18/97		13%	81%	41%	60%	55%	40%	64%	57%
07/30/98		28%	66%	44%	39%	46%	45%	65%	51%

* This average includes the July data for M-3 and M-4.

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Cross Section Measurement for Debris Field Transects

Figure 3.21 shows the mean bed elevation for each of the debris series transects from September 1993 to August 1998. All data were normalized to use the September 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.22 shows the average relative bed elevation for D-1 through D-5 transects. Table 3.20 summarizes the response of each transect. These transects have exhibited more total scour than either the RT or mixer cross-sections and have not stabilized. The pattern of scour during peak runoff and refill on the descending limb is similar to the pattern seen in the mixer, although there is less re-fill for more total net scour.

Table 3.21 presents the cobble percentages during each survey for the debris field series cross-sections. Cobble percentages are generally lower than either the RT or mixer series transects with not significant change with flow or time.

Cross Section Measurement for Clay Hills Transects

Figure 3.23 shows the mean bed elevation for each of the Clay Hills transects from October 1993 to August 1998. All data were normalized to use the October 1993 survey as the baseline and the relative elevation of each transect was set to 1.0 meter for that survey.

Figure 3.24 shows the average relative bed elevation for C-1 and C-2 transects. These transects are located in a canyon reach that is influenced by Lake Powell. There is about 40 ft of sand deposited in the bottom of the canyon in this location, so the river bottom is very mobile. The thalweg is constantly shifting by eroding and depositing sand shoals. Most of the change in the two cross-sections through July 1996 is a result of this erosion and deposition within the cross-sections.

Beginning in 1996, the elevation of the downstream cross-section (C-2) began increasing. C-1 began increasing in 1997. Both are at maximum (approximately 0.65 m higher than the initial surveys) in the fall of 1998. Prior to 1995, Lake Powell levels were sufficiently low to not influence this reach. Even though the lake levels were low, rerouting of the channel at RM 0 placed the channel on a sandstone ledge, preventing erosion upstream. In 1995 lake levels reached a level sufficient to submerge the waterfall that had developed at the ledge, but did not markedly impact channel elevations upstream until 1996. Since that time, the bed elevation has been gradually increasing in response to this backwater effect. A plot of Lake Powell water surface elevation is shown in Figure 3.25. Also shown is the approximate elevation of the waterfall.

Substrate is 100% sand for both of these transects and will remain so regardless of the elevation of the bed. The changes in bed elevation in this reach (below RM 18) are more influenced by Lake Powell than San Juan River discharge.

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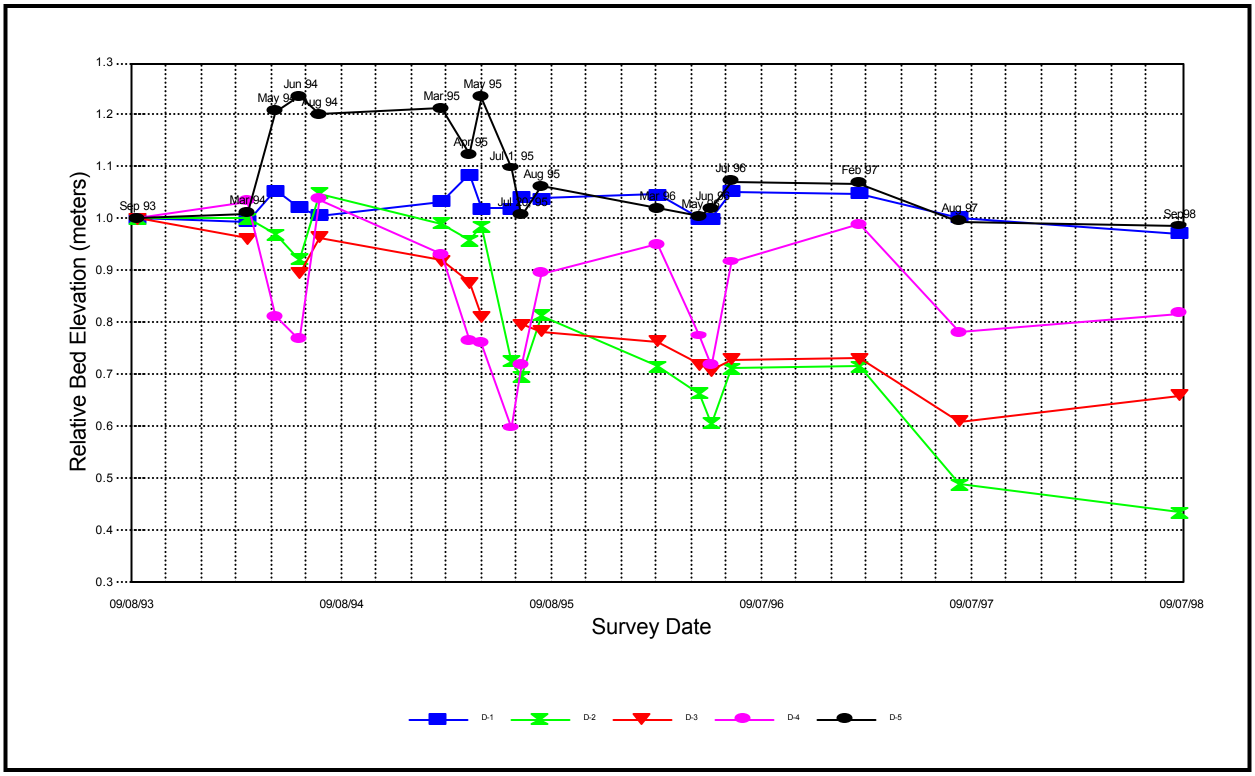

Figure 3.21. Releative bed elevation for all Debris Field series transects on the San Juan River (1993-1998).

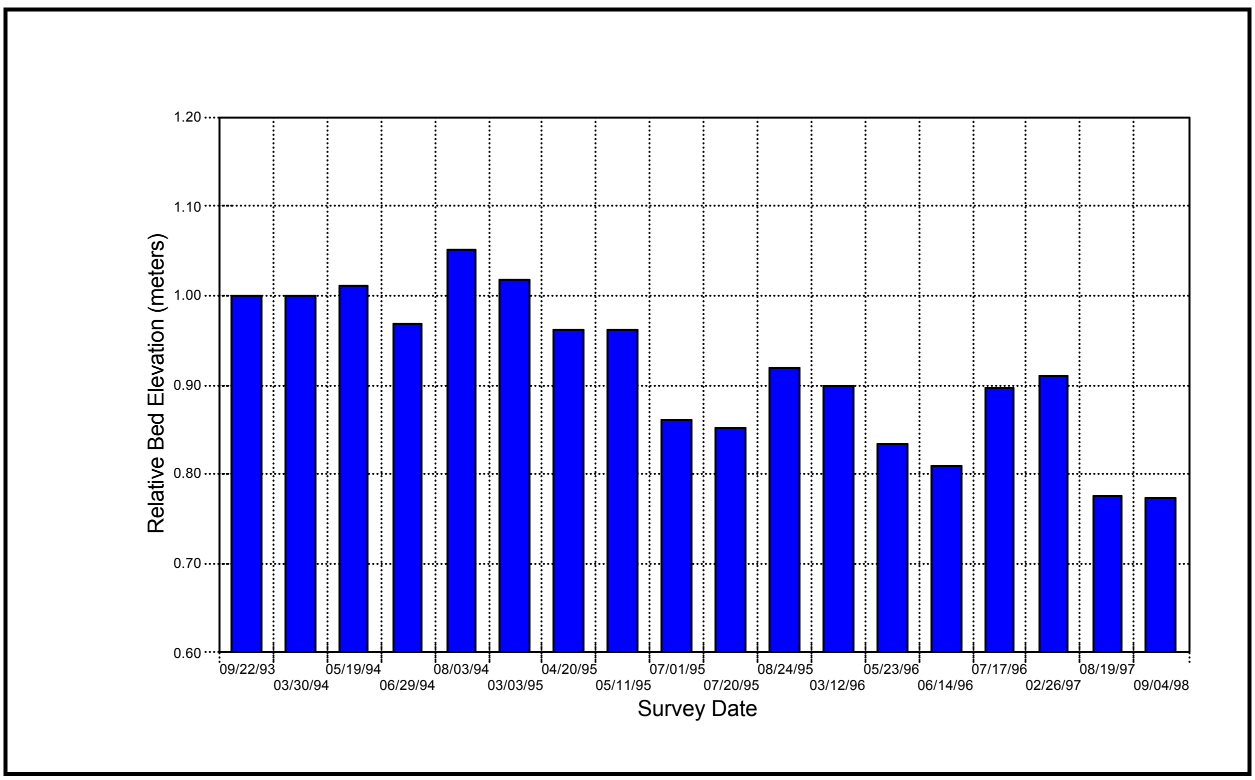

Figure 3.22. Average relative bed elevation for Debris Field series transects on the San Juan River (1993-1998).

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Table 3.20. Summary of debris field series transect changes with time.

Transect	Net Change- m 9/83-8/98	Description of the Pattern of Change
D-01	-0.03	Relatively stable, with some deposition until '97, sour in '97 and '98
D-02	-0.57	Heavy scour in '95 and '97, some re-fill on descending limb, net scour each year except '96.
D-03	-0.34	Similar to D-02, except filled slightly in '98.
D-04	-0.18	Heavy scour through peak, large refill on descending limb, little net change until scour in '97.
D-05	-0.01	Large fill in '94, minor fill in '96, heavy scour in '95, small scour in '97, no change in '98
MEAN	-0.23	General pattern of scour at peak runoff and refill on descending limb. Greatest net scour in 1995 and 1997. Tend to be erosional on ascending limb and during peak runoff.

Table 3.21. Percent cobble substrate for the debris field series transects on the San Juan River (1993-1998).

Date	D-1	D-2	D-3	D-4	D-5	Average
09/22/93	34%	22%	16%	16%	19%	21%
03/30/94	28%	20%	14%	9%	21%	19%
05/19/94	36%	38%		22%	51%	29%
06/29/94	21%	25%	13%	4%	34%	19%
08/03/94	34%	24%	5%	4%	30%	19%
03/03/95	24%	29%	9%	5%	17%	17%
04/20/95	25%	29%	13%	8%	28%	20%
05/11/95	21%	29%	8%	9%	42%	22%
07/01/95	22%	15%		23%	43%	21%
07/20/95	30%	10%	43%	7%	21%	22%
08/24/95	25%	11%	43%	7%	8%	19%
03/12/96	25%	12%	40%	3%	40%	24%
05/23/96	27%	18%	43%	2%	26%	23%
06/14/96	27%	14%	44%	3%	12%	20%
07/17/96	26%	15%	48%	1%	28%	24%
02/26/97	21%	9%	34%	6%	28%	20%
08/19/97	33%	14%	29%	14%	17%	21%
09/04/98	37%	26%	31%	13%	23%	26%

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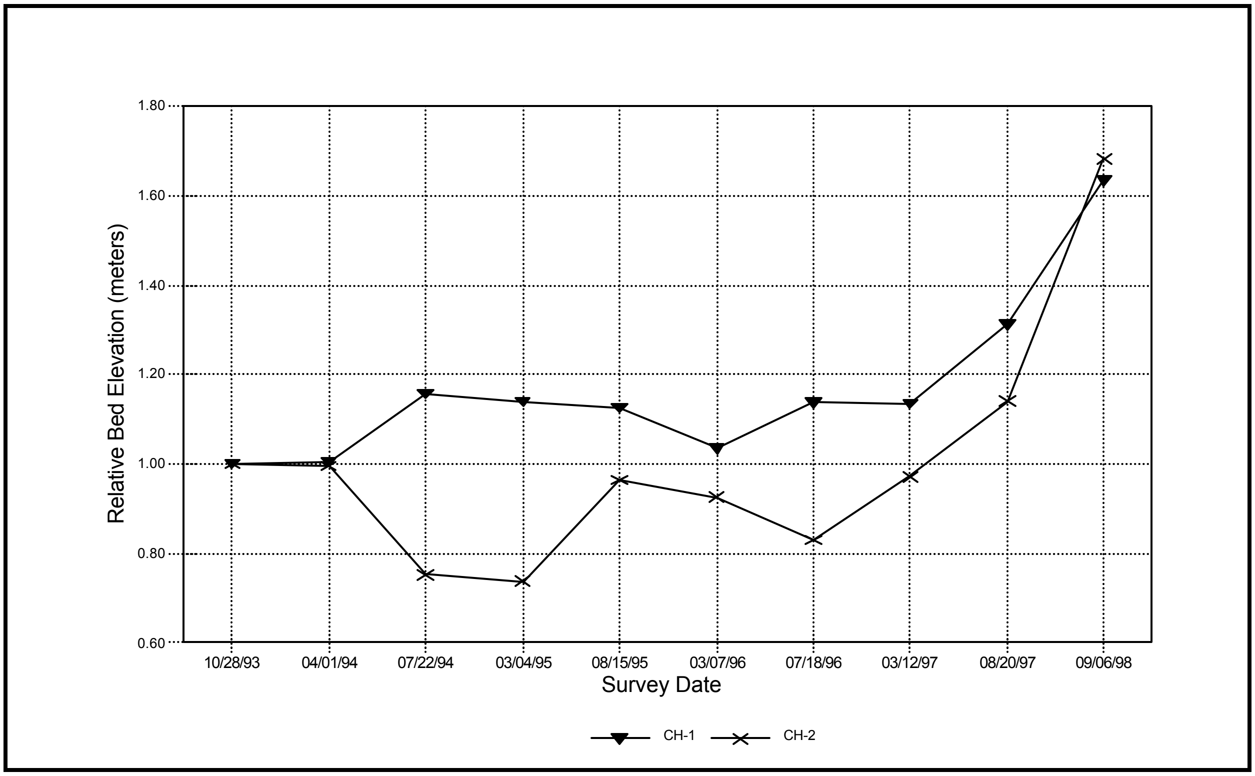

Figure 3.23. Relative bed elevation for the two Clay Hills series transects on the San Juan River (1993-1998).

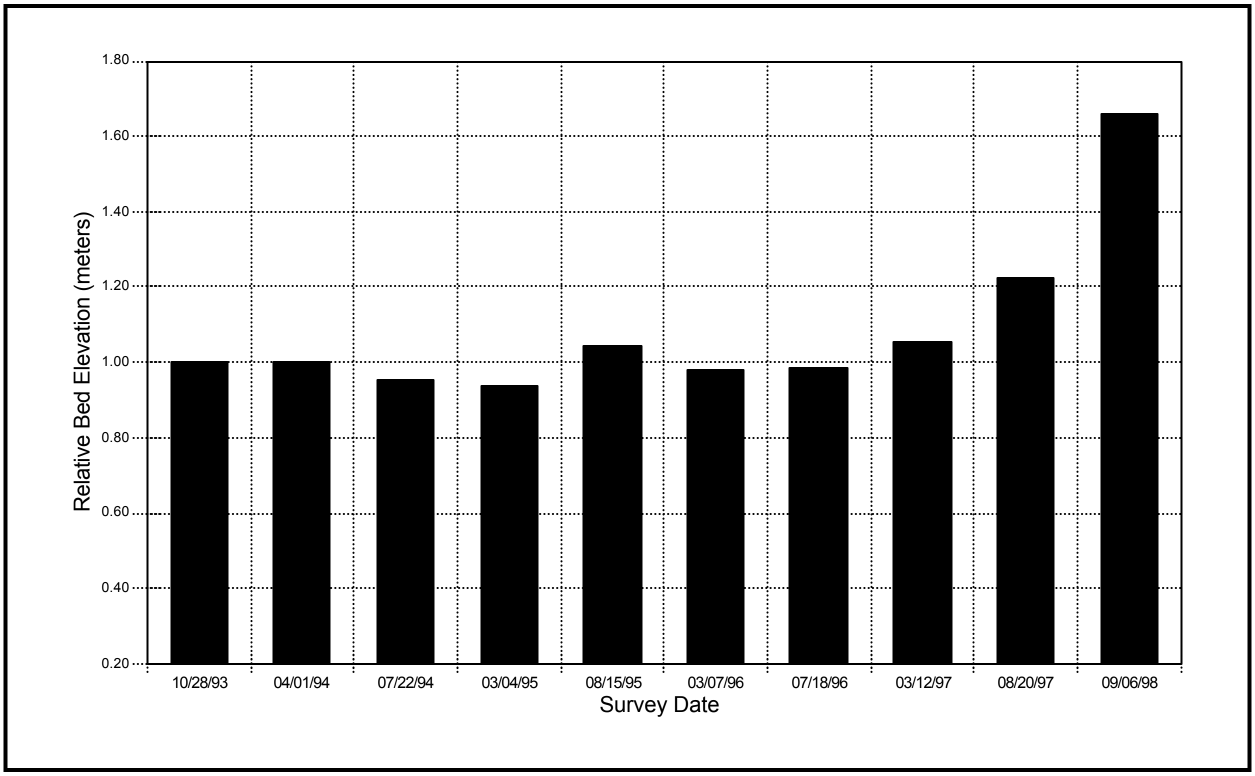

Figure 3.24. Average relative bed elevation for Clay Hills series transects on the San Juan River (1993-1998).

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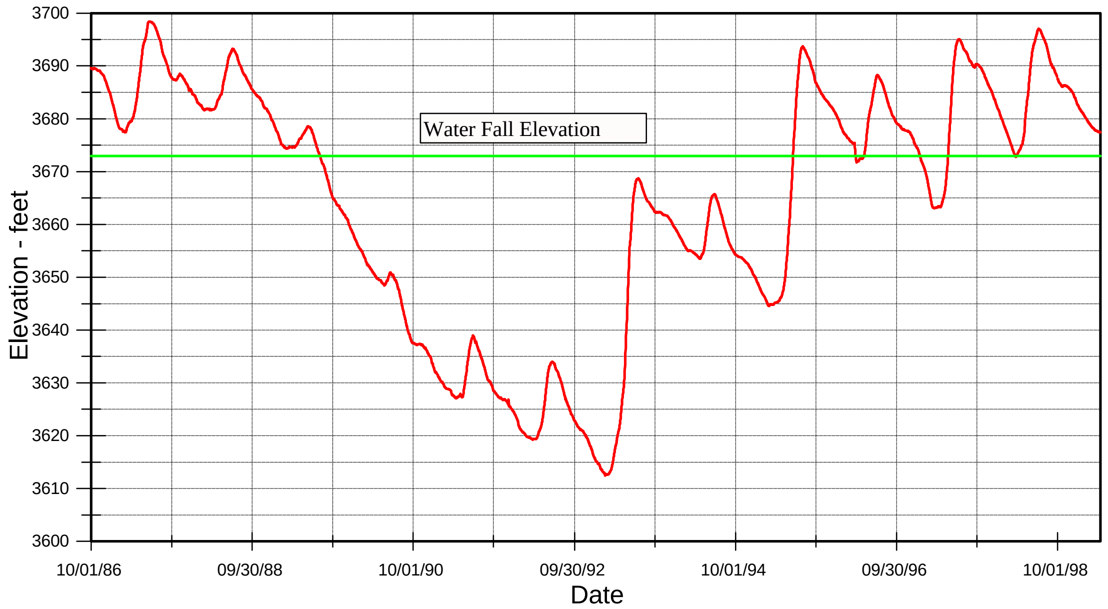

Figure 3.25. Lake Powell water surface elevation (1986-1998).

Channel Response to Flows at USGS Gage Locations

Upon analysis of the data, only the San Juan River at Farmington and San Juan River at Shiprock data could be used. The early records at Bluff were not available, limiting the record to a period too short to be useful. At Archuleta, a portion of the measurements were made by wading and a portion from the cableway. There appears to be a different datum for the two surveys that could not be reconciled, as the elevations between the two methods were consistently different. While there were difficulties in interpreting and adjusting the data from Farmington and Shiprock, the resulting data set used is felt to be sufficiently accurate to allow assessment of the long-term response of the channel at these to locations.

The relative bed elevation at the Farmington gage is shown in Figure 3.26 for the period 1942 - 1996. The baseline elevation of 1.0 m was assigned to the April 1942 data point and all subsequent elevations computed from this baseline. Only April and June elevations are shown, representing pre- and post-runoff. The same information is shown in Figure 3.27 for the Shiprock gage for the period 1943 - 1996. The date of Navajo Dam influence is shown on each plot along with the beginning of the re-operation to mimic a natural hydrograph.

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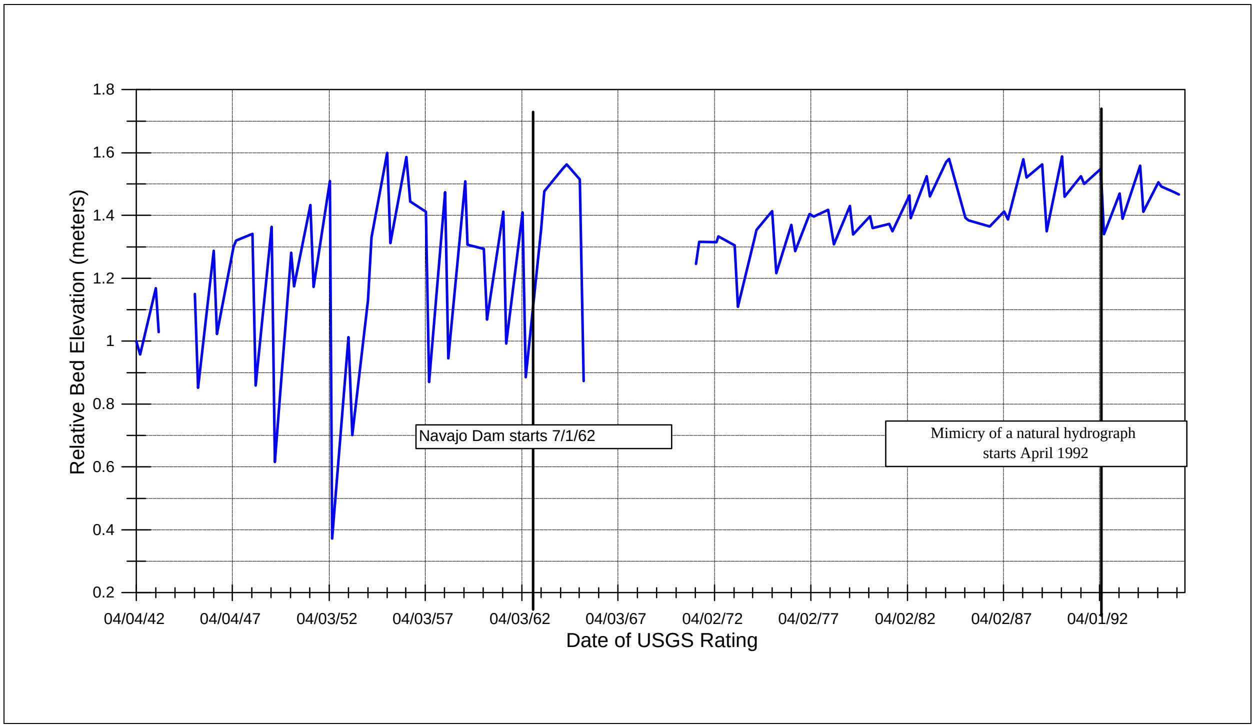

Figure 3.26. Mean relative bed elevation at the San Juan River at Farmington gage (1942-1996).

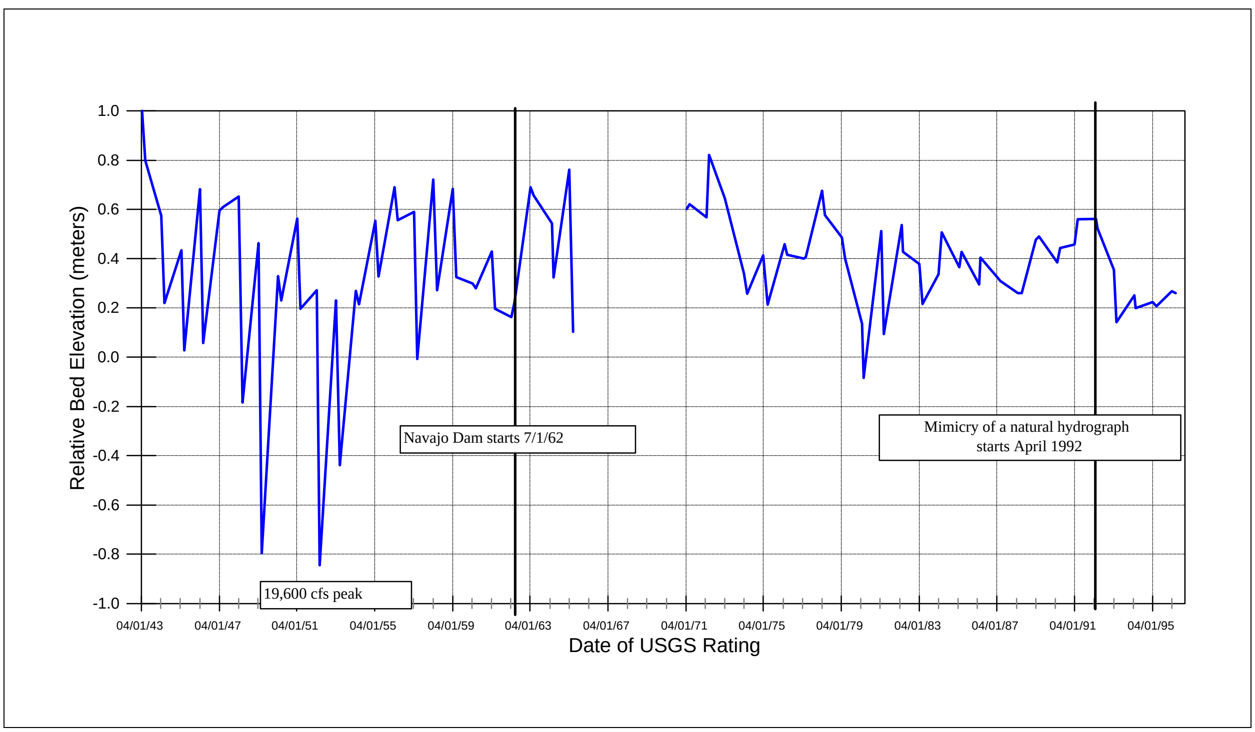

Figure 3.27. Mean relative bed elevation at the San Juan River at Shiprock gage (1943-1996).

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Both plots indicate that the extremes in elevation before and after runoff are influenced by the peak magnitude and volume of runoff. As such, there appears to be less variability after closure of Navajo Dam than before, but the difference is more marked for Farmington than Shiprock. There does not appear to be any significant shift of long term scour or deposition due to Navajo Dam influence. Farmington shows a general depositional trend with time, before and after Navajo Dam. Shiprock does not exhibit any statistically significant trend.

There appears to be a minor shift downward in each graph at the beginning of re-operation in 1992, although the trend has not changed after this shift. The shift is more marked for Shiprock than Farmington, reflecting the more dynamic nature of this site. This shift is similar to the results seen at the RT transects. When comparing the amount of shift to the long term patterns, there does not appear to be a concern that any serious channel degrading is occurring. The minimum elevations after re-operation are still above the minimums during the post-dam period and well above the minimums for the pre-dam period.

Substrate Movement at Surveyed Cross-Sections

Both scour and deposition occurred at all cross-sections and during all survey periods, at flows as low as 2,500 cfs, the lowest maximum flow between surveys. In addition, cobble movement (both scour and deposition) occurred at some point in most of these cross-sections at all flows. Table 3.22 summarizes the scour and deposition between survey points for the RT and Mixer cross-sections, including the portion of each that is cobble. Also shown in the table are the hydrographic parameters of the flow recommendation and the linear correlation parameters for each to scour and deposition.

The strongest correlation with total scour and any of the hydrographic conditions is with days above 5,000 cfs ($R^2 = 0.82$, $n = 12$, $p < .01$). There is also a reasonable correlation between peak discharge and days above 2,500 cfs. The correlation improves only slightly when all hydrographic parameters are included.

The correlation between deposition and the hydrographic conditions is not as strong, with days above 8,000 cfs being the best ($R^2 = 0.59$, $n = 12$, $p < .01$). There is significant improvement in the correlation when all parameters are used.

The cobble movement correlations are not as strong, with only three of the parameters significant at the 95% level. Cobble movement (deposition and scour) is most strongly correlated to days above 5,000 cfs, although the correlation is weak. The correlation improves for both scour and deposition when all hydrographic parameters are included in the analysis.

The mixer transects have more variability than the RT transects and the correlations are not as good. In this case, the deposition correlations are better than those for scour for total movement and the opposite for cobble movement. There are no significant correlations for cobble scour, and the cobble deposition relationships are weak.

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Table 3.22. Average deposition and scour (total and cobble) at RT and Mixer series transects in the San Juan River (1992-1998) as related to hydrographic conditions.

Period	Total -m^3/m		Cobble - M^3/m		Peak	Days	Days	Days	Days	combined
	Scour	Deposition	Scour	Deposition	cfs	> 10000	> 8000	> 5000	> 2500	
RT cross-sections										
Mar-Jul 92	9.4	7.1	0.3	1.9	8,900	0	3	54	81	
Jul 92 - Feb 93	5.2	6.9	0.8	0.7	3,490	0	0	0	9	
Feb - Jul 93	14.0	5.1	4.0	2.9	10,300	1	16	109	128	
Jul 93 - Mar 94	3.9	8.1	1.4	1.0	4,700	0	0	0	6	
Mar 94 - Aug 94	7.5	2.7	1.1	0.8	10,000	0	13	49	67	
Aug 94 - Mar 95	3.2	6.4	0.6	0.5	2,820	0	0	0	1	
Mar 95 - Aug 95	8.8	2.8	1.8	1.6	12,100	11	27	72	135	
Aug 95 - Mar 96	1.6	6.9	0.6	1.1	2,490	0	0	0	0	
Mar 96 - Jul 96	4.6	3.6	0.9	0.5	3,540	0	0	0	36	
Jul 96 - Feb 97	2.0	7.2	0.4	0.9	2,510	0	0	0	1	
Feb 97 - Aug 97	10.6	2.7	2.3	1.1	11,900	10	29	49	98	
Aug 97 - Aug 98	3.4	8.4	0.9	1.9	8,300	0	2	33	78	
Correlation coefficient - total scour					0.67	0.22	0.55	0.82	0.72	0.84
Significance of f statistic (p) - total scour					<.01	0.12	0.01	<.01	<.01	0.02
Correlation coefficient - total deposition					0.33	0.40	0.59	0.20	0.30	0.83
Significance of f statistic (p) - total deposition					0.05	0.03	<.01	0.14	0.07	0.03
Correlation coefficient - cobble scour					0.36	0.09	0.47	0.58	0.45	0.73
Significance of f statistic (p) - cobble scour					0.04	0.17	0.02	<.01	0.02	0.08
Correlation coefficient - cobble deposition					0.34	0.02	0.12	0.69	0.53	0.89
Significance of f statistic (p) - cobble deposition					0.04	0.70	0.28	<.01	0.01	0.01
Mixer cross-sections										
Feb - Apr 93	8.7	4.4	1.5	0.1	6,720	0	0	25	39	
Apr - Jun 93	19.1	4.8	0.2	3.8	10,300	3	16	67	67	
Jun - Jul 93	3.0	5.8	3.2	1.6	7,360	0	0	9	16	
Jul 93 - Mar 94	2.2	4.5	2.1	1.3	4,700	0	0	0	6	
Mar 94 - May 94	3.7	7.2	3.8	1.5	6,600	0	0	7	14	
May 94 - Jun 94	5.6	7.5	3.4	1.7	10,000	0	13	41	41	
Jun 94 - Aug 94	4.7	2.0	0.2	2.4	5,460	0	0	1	12	
Mar 95 - Aug 95	4.7	6.3	3.2	2.0	12,100	11	27	72	135	
Aug 95 - Mar 96	1.4	2.6	1.5	0.7	2,490	0	0	0	0	
Mar 96 - Jul 96	3.0	1.8	0.8	1.1	3,540	0	0	0	36	
Jul 96 - Feb 97	2.0	2.1	0.7	0.7	2,510	0	0	0	1	
Feb 97 - Aug 97	6.8	10.7	5.0	3.4	11,900	10	29	49	98	
Aug 97 - Jul 98	7.7	4.7	2.3	2.3	8,300	0	2	33	78	
Correlation coefficient - total scour					0.3	0.04	0.15	0.47	0.18	0.71
Significance of *f* statistic (p) - total scour					0.05	0.52	0.2	0.01	0.14	0.07
Correlation coefficient - total deposition					0.63	0.35	0.48	0.33	0.28	0.82
Significance of *f* statistic (p) - total deposition					<.01	0.03	0.01	0.04	0.06	0.01
Correlation coefficient - cobble scour					0.31	0.23	0.24	0.09	0.15	0.66
Significance of *f* statistic (p) - cobble scour					0.05	0.1	0.09	0.33	0.19	0.12
Correlation coefficient - cobble deposition					0.47	0.26	0.41	0.39	0.3	0.51
Significance of *f* statistic (p) - cobble deposition					0.01	0.07	0.02	0.02	0.05	0.31

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These relationships are somewhat different than those reported in the Flow Recommendation Report. This table includes the 1998 data and a correction to some of the values for the RT transects. Further, the values reported in the flow recommendation are listed as m^3/m, whereas they are actually ft^3/ft. These changes do not change the conclusions in the flow recommendation report.

Flow Modification Impact on Channel Complexity

Figure 3.28 shows the relationship between the number of islands in Reaches 3 to 5 and discharge during each of the mapping periods. Two regression lines are shown. The longer line represents the full range of discharges encountered. The shorter line includes only flows below 1,200 cfs to represent low flows. It is theorized that channel complexity at low flow would show change first if channel simplification was occurring because of channel scour. As expected, the number of islands increases with increased flow up to about 6,500 cfs as more secondary channels become active. The substantial drop in number of islands between 6,500 and 7,700 cfs indicates overbank flooding at this discharge as inundated islands are flooded and become mapped as flooded vegetation.

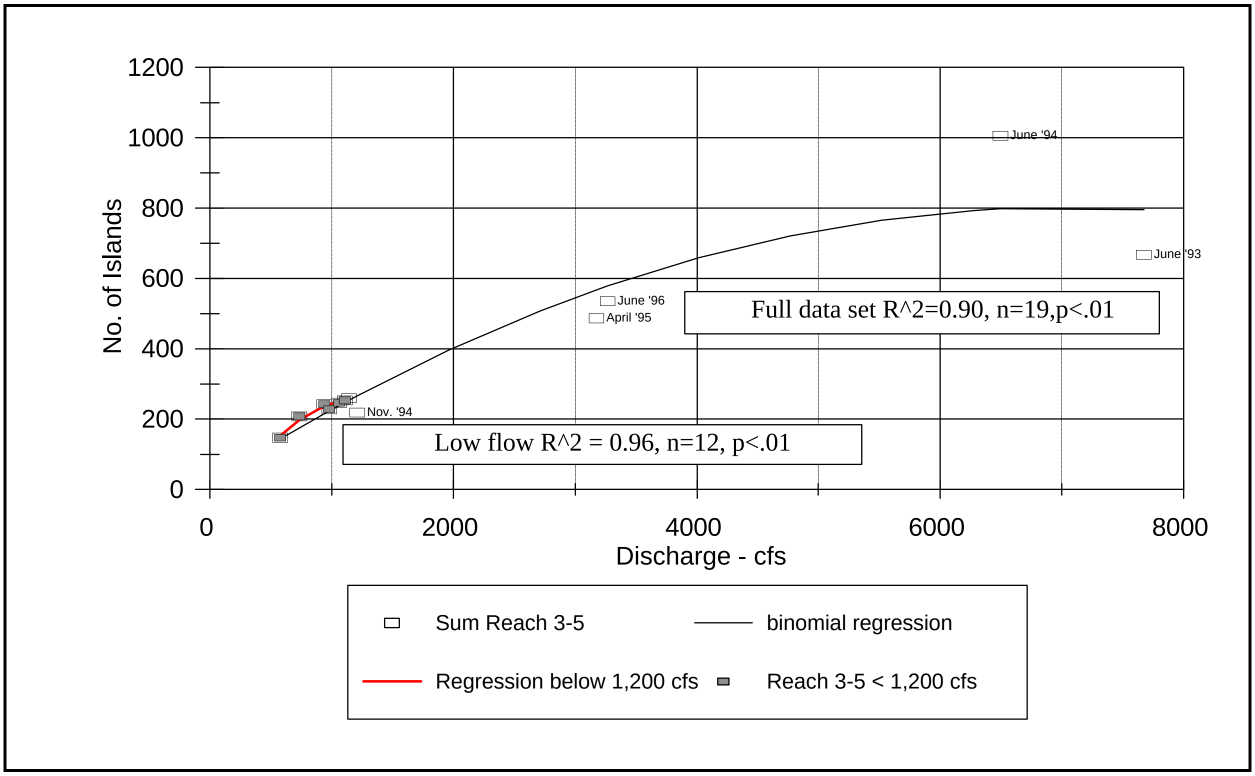

Figure 3.28. Relationship between main channel flow and island count.

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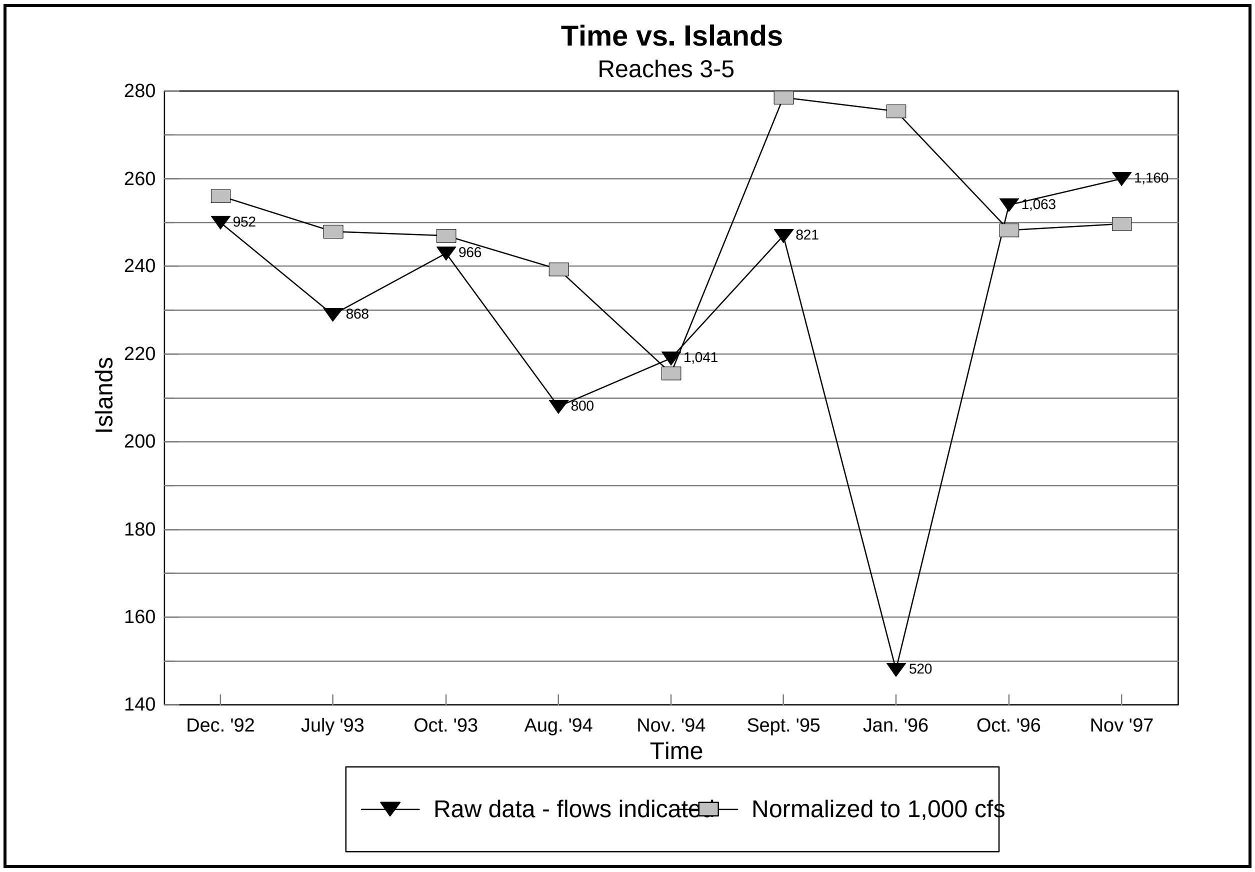

Figure 3.29 Island count in Reaches 3, 4, and 5 at base flow vs. time as a measure of change in channel complexity.

To examine the chronological effect of the flow regime on the number of islands throughout the 7-year research period (a test of channel simplification), the total number of islands in Reaches 3, 4, and 5 was plotted against time as noted by the triangles in Figure 3.29. The first data set plotted represents the actual number of islands at the noted flow for each mapping, with only the mapping runs completed at flows below 1,200 cfs shown. Any variation in island count because of channel simplification for this data set is masked by the change in flow rate during mapping. To determine if a change occurred, the island counts had to be standardized to a common flow. These normalized island counts are represented as squares on the second line. Normalized island counts for each year were computed as the ratio of the island counts predicted by the regression equation (represented by shorter line on Figure 3.28) for a flow of 1,000 cfs, to that ratio predicted at the flow shown in Figure 3.29 times the actual number of islands mapped at the flow shown. The analysis indicates a small reduction in islands through 1994, an increase in 1995, a subsequent decrease in 1996, and a slight increase in 1997 with no net change over the 6-year period. The scour indicated by the decrease in mean channel elevation at the measured cross-sections would indicate an imbalance that could lead to channel simplification (loss of multiple channels and islands). For this short period of record, it appears that there was no significant loss of channel complexity associated with the

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channel scour observed, although there appears to have been a short-term loss that was regained during the high-flow condition in 1995.

During 1995, for the first time in the 7-year research period, flows exceeded 10,000 cfs for more than 1 day, achieving a daily peak flow of 12,100 cfs with flows above 10,000 cfs for 11 days at Four Corners. The first increase in islands was exhibited in 1995. The indication from this flow series is that maintaining peak flows near channel capacity (1992 to 1994) may have slightly simplified the channel, while a larger overbank flow (1995) appears to have developed additional channels and islands, reversing the simplification. Some channel complexity may be lost because of summer and fall sediment-laden storm events that tend to berm off small flow-through and secondary channels (August 1994 to November 1994), and runoff events with peaks below 5,000 cfs (1996) may cause loss of channel complexity through the same process. The year 1997 was the only other year with flows above 10,000 cfs and the only other year to exhibit an increase in island count, although the increase is small relative to 1995. This is due in part to large summer sediment inflow between runoff and mapping that refilled small secondary channels in 1997.

Loss of channel complexity is of concern not only as an indicator of channel incision and loss of secondary channels, but because of the potential impact on habitat diversity. Figure 3.30 plots the average Shannon-Weaver habitat diversity index for Reaches 3-5 with non-normalized island count for the flows below 1,200 cfs from 1992 through 1997. The patterns are not the same, but habitat diversity did increase somewhat in 1995 following runoff after a decline in 1994. In general, habitat diversity has not decreased during the period of test flows, corresponding with general trend in island count. However, it appears that habitat diversity is related to processes other than channel complexity. The greatest diversity existed in 1993 after prolonged runoff and again after the high flows in 1997. This change is likely not significant however. Habitat diversity for the number of habitat categories mapped can range from 0 to 1.49 (log of the number of habitats). During the study they ranged from 0.83 to 0.96, a relatively small variation and likely within mapping error.

Habitat diversity was regressed against island count for the three reaches and seven mappings in the data set to determine the existence of a relationship. While there was a positive correlation between island count and habitat diversity it was very weak ($R^2 = 0.14$, $p=0.08$). By removing the two winter values (December 92 and January 96) the relationship improved ($R^2 = 0.42$, $p=0.001$), but was still not strong. Obviously, other mechanisms influence habitat diversity as strongly as island count.

While analysis of the trend in island areas seems to indicate that the net effect of the research flows has not been damaging to channel complexity or habitat diversity and that flows above 10,000 cfs are important in maintaining channel complexity, 5 years is a short period of record with which to identify long-term trends. Long-term monitoring will be required to assess the effects of restoration of a more-natural hydrograph on channel complexity.

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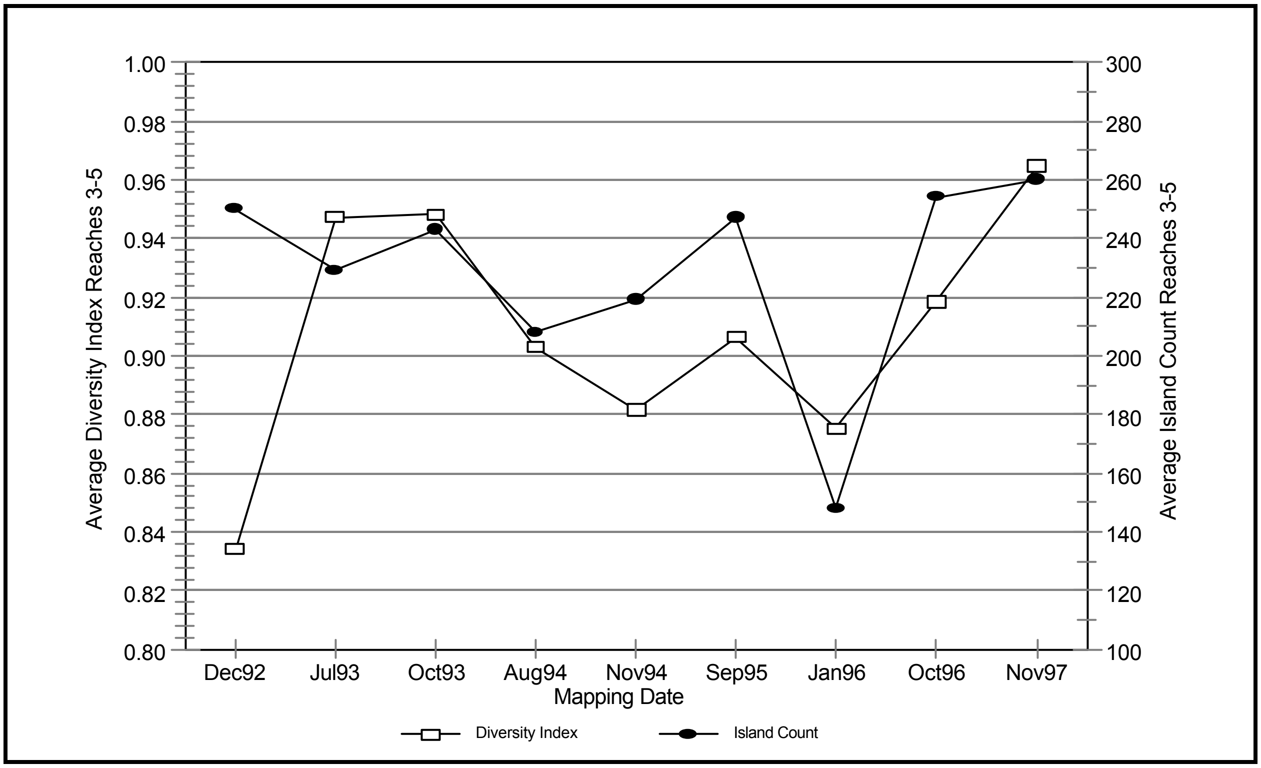

Figure 3.30. Habitat Diversity and Island Count in the San Juan River at flows below 1,2000 cfs, 1992-1997

Bankfull Channel Capacity

A summary of bankfull discharges for the reaches modeled with HEC-RAS is presented in Table 3.23. In the lower three reaches, overbank flow occurred first (indicated by overbank conditions at one transect) at discharges between 7,100 and 7,500 cfs, based on calibrated HEC-RAS modeling. At RM 174, the first transect to show overbank flow occurred at 10,000 cfs. At least two cross-sections in each reach experienced overbank flow between 8,000 and 8,500 cfs for all study reaches except

RM 174, which required 10,500 cfs for overbank flow at two cross-sections. Therefore, bankfull was assessed to be between 7,100 and 10,000 cfs, depending on the study reach. While this discharge is greater than that estimated based on island counts and flooded vegetation for 1993 and 1994, the ranges overlap. If a real difference exists between the beginning and ending of the 7-year research period, it could be partly explained by an increase in channel capacity because of bed scour between 1993 and 1996. However, conclusions based on such a short time period should be considered preliminary, and continued monitoring is necessary to verify an actual change in channel capacity. If channel capacity has increased, the change can be considered relatively insignificant, especially because a concurrent change in channel complexity was not detected. While modeled reaches exhibited initiation of overbank flow at between 7,100 and 10,000 cfs, consistent overbank flow occurred at between 8,000 and 10,500 cfs. The median overbank flow for the 20 cross-sections

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Table 3.23. Bankfull discharge from HEC-RAS modeling of four 0.25 mile (mi) reaches in the San Juan River between River Mile (RM) 133 and RM 174.

REACH DESIGNATION	BANKFULL FLOW AT ONE CROSS-SECTION (CFS)	BANKFULL FLOW AT TWO OR MORE CROSS-SECTIONS (CFS)
RM 133	7,500	8,000
RM 167	7,100	8,000
RM 169	7,100	8,500
RM 174	10,000	10,500

modeled was 9,000 cfs. However, the nature of the areas modeled was such that when flows were overbank on more than 25% of the area, any increase in stage (height of water) with increased flow was small. In some areas, the floodplain sloped away from the river channel, allowing the overbank flow to spread out and reenter the channel at a downstream location. In other locations a low, flat floodplain was separated from the river by a short berm, allowing a large increase in flow area for a small change in stage. Based on this information, bankfull discharge for the San Juan River was set at 8,000 cfs (25% of cross-sections overbank) as the value that appeared to fit most of the study area.

The mean bankfull discharge for the RT cross-sections was computed to be 7,300 cfs (range 5,300 to 9,900 cfs) prior to modification of the flows (1992). After 6 years of research flows designed to mimic a natural hydrograph, the mean bankfull discharge was computed to be 8,200 cfs (range 5,800 to 12,600 cfs) for an increase of 12% from pre-research conditions. The 8,000-cfs channel capacity determined from the modeling studies is supported by the results of this analysis and the perceived change in channel capacity over the research period confirmed.

In summary, the bankfull discharge of the San Juan River is about 8,000 cfs and has increased by about 12% since the beginning of the research period. Bankfull flow is considered the practical upper limit for maintenance of cobble transport through low-gradient reaches and is considered in the analysis of cobble bar maintenance in the next section. Flows above 10,000 cfs appear to be important for maintaining channel complexity and floodplain integrity. Continued monitoring will be necessary to verify these values and assess impacts of the restoration of a more-natural hydrograph on channel complexity and capacity.

Cobble Bar Characterization

From the substrate characterization at each cross-section, it is clear that substantial cobble movement has taken place during each of the 6 years measurements have been taken. This qualitative assessment does not allow good predictive capability or characterization of the conditions that exist in suspected spawning locations. The detailed radio tracking completed by Miller Ecological Consultants in the summers of 1993 and 1994 allowed identification of these suspected spawning locations and a characterization of the substrate in these areas. In 1994, the results from these sites

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were compared to known spawning areas on the Yampa River and a suspected site on the Colorado River in Grand Junction, Colorado to assess the suitability of substrate for spawning at these locations. Similarity would suggest suitability. However, dis-similarity would not necessarily indicate unsuitability, since it may be possible for successful spawning in substrate with characteristics different than those seen on the Yampa river. The sites did exhibit similar characteristics, except that the cobble size at the Colorado River site was larger than at the other locations. In 1995, the conditions at 13 locations were compared to the Yampa and Colorado data and to previous data at the suspected spawning sites in the San Juan in an attempt to identify other locations for potential spawning. Subsequently, two suspected spawning locations and two potential spawning locations located upstream of the suspected sites have been monitored annually.

Characterization of Bed Material Size in Suspected Spawning Bars

Table 3.24 summarizes the cobble size distribution for each of the bars analyzed in 1995. For comparison purposes, 1994 data from the suspected spawning locations and the Yampa data are included in the table. The average of all bars is very similar to the Yampa site and many of the individual sites are also very similar. In general, the cobble size is not correlated to river mile in the range sampled (76.6 - 173.7) with no increasing or decreasing trend. There is appreciable variability from site-to-site, however.

Table 3.25 shows the same size distribution characteristics for the interstitial sediments sampled from each bar. The distributions are for the material passing a 12.5 mm screen. Again, the variability seen is somewhat random with respect to position on the river and the size does not appear to be correlated to the cobble size. For example, the site with the largest interstitial material has a smaller than average D50 cobble size and the site with the smallest interstitial material has cobble similar in size to the site with the largest interstitial material.

Subsequent surveys were completed from 1996 through 1998 for the two suspected spawning bars and the two potential upstream bars. The results are summarized in Table 3.26. The variation from year-to-year is believed to represent sampling error rather than any response to flows. In 1996, the flows were lower than the other years, so it is unlikely that the bars would have had larger cobble. Sampling error is enhanced in these conditions as the samples are taken under water. Also, the same location on the bar may not be sampled each year due to differences in flow rate and water depth which affect accessability to areas of the bar. Each of these conditions affect the accuracy of the measurement and explain some of the variability in results form year-to-year.

In 1998, the measurement method was changed from ruler measurement of the intermediate cobble dimension to the use of a template with square holes representing 1 cm increments in size. A test of 460 cobbles taken at the same locations and by the same methods used in this study was conducted to compare the results of the two methods. Figure 3.31 compares the size distribution of the same sample from the two methods. There appears to be about a 10% difference in the D_{50} for the 2 methods, with the measured method over-predicting. Figure 3.32 plots the ruler measurement

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Table 3.24. Cobble size distribution for potential spawning sites from 1995 survey.

Date	River Mile	Site	Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm				
			D84	D75	D50	D25	D16
07/28/95	173.70	173	125	114	72	54	45
07/28/95	172.00	171	120	105	75	53	43
07/27/95	169.00	169A	90	79	60	44	41
07/27/95	168.40	168C	128	109	78	54	51
07/27/95	168.40	168B	118	111	74	58	50
07/27/95	168.40	168A	115	103	78	58	51
07/28/95	163.00	163	123	114	90	65	55
07/28/95	137.70	137B	105	95	70	54	45
07/28/95	137.30	137D	145	138	90	64	58
07/25/95	132.00	132-23	88	75	60	43	36
07/25/95	132.00	132-21	61	52	38	29	26
07/25/95	132.00	132-25	100	92	63	42	36
07/25/95	132.00	132-20	98	83	61	40	35
07/26/95	131.20	132-124	75	63	47	31	24
07/26/95	131.20	131-32	88	63	50	32	21
07/26/95	131.90	131-33	57	53	40	24	21
07/30/95	109.80	109	130	118	80	54	49
07/29/95	88.00	88	104	95	82	61	52
07/29/95	82.95	82A	78	72	61	49	42
07/29/95	82.90	82B	158	139	112	74	65
07/29/95	82.85	82C	90	72	59	46	40
07/29/95	78.00	78	130	114	89	74	71
07/29/95	76.60	76	124	121	101	79	71
	Average		106	95	71	51	45
	Yampa		110	94	76	58	46
	Colorado		125	104	78	49	38
	132-94		100	79	65	52	46
No. of sites exceeding Yampa size			11	13	9	7	10
% of sites exceeding Yampa size			47.8%	56.5%	39.1%	30.4%	43.5%

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Table 3.25. Size distribution of interstitial material at selected cobble bars from 1995 survey.

	Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm				
Site	**D84**	**D75**	**D50**	**D25**	**D16**
173.7	9.34	4.84	2.62	0.92	0.66
172	9.17	4.78	2.11	0.87	0.62
169	10.58	5.29	6.49	2.59	1.15
168.4 C	9.48	4.89	3.07	0.98	0.70
168.4 B	9.71	4.98	3.79	0.93	0.57
168.4 A	10.30	5.19	5.63	1.47	0.98
163	10.13	5.13	5.11	1.21	0.81
137.4	9.96	5.07	4.56	1.11	0.76
137.7	8.03	4.36	1.25	0.59	0.43
132 #21	9.45	4.88	2.98	0.44	0.34
132 #25	10.21	5.16	5.33	0.78	0.40
132 #23	10.10	5.12	4.99	1.03	0.48
132 #20	8.75	4.62	0.77	0.35	0.26
131 #124	9.77	5.00	3.97	0.69	0.40
131 #33	10.11	5.12	5.02	1.18	0.59
131 #32	8.70	4.60	0.63	0.33	0.28
109	9.48	7.78	2.36	0.87	0.55
88	10.57	9.49	6.48	0.87	1.01
82.85 C	9.51	7.82	3.42	1.05	0.58
82.9 B	9.03	7.08	1.59	0.79	0.49
82.95 A	3.53	1.59	1.17	0.75	0.60
78	9.71	4.97	3.77	1.12	0.71
76.6	7.12	4.02	1.31	0.77	0.57
Maximum	10.58	9.49	6.49	2.59	1.15
Minimum	3.53	1.59	0.63	0.33	0.26
Average	9.37	7.61	2.71	0.76	0.46

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Table 3.26. Cobble size distribution for two suspected and two potential spawning bars in the San Juan River, 1995-1998.

		Cobble Diameter Associated with the Indicated "Percent Passive" Size Category mm				
Site	**Year**	**D84**	**D75**	**D50**	**D25**	**D16**
M-4 (131.2)	1995	65	54	42	28	21
M-4	1996	108	98	80	66	56
M-4	1997	79	71	52	36	28
M-4	1998	85	70	46	25	19
Average		84	73	55	39	31
M-6 (132)	1995	86	73	51	34	27
M-6	1996	116	106	78	55	46
M-6	1997	99	84	66	49	44
M-6	1998	95	82	59	37	30
Average		99	86	63	44	37
1684	1995	110	102	72	49	46
1684	1996	146	126	84	50	46
1684	1997	105	100	63	43	37
1684	1998	112	99	68	47	36
Average		118	107	72	47	41
1737	1995	n/a	n/a	n/a	n/a	n/a
1737	1996	99	80	48	30	26
1737	1997	126	80	38	22	17
1737	1998	120	103	70	47	39
Average		115	88	52	33	27

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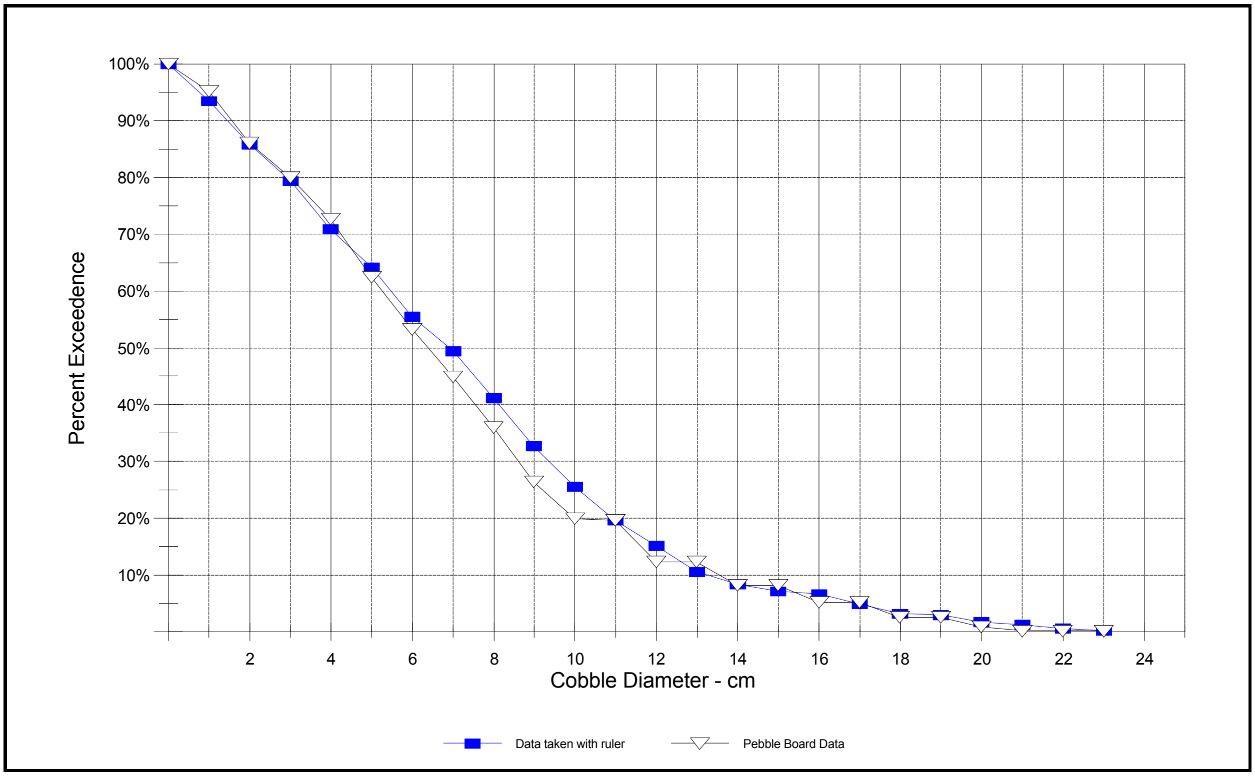

Figure 3.31. Cobble size frequency distribution for ruler and template measured cobble samples.

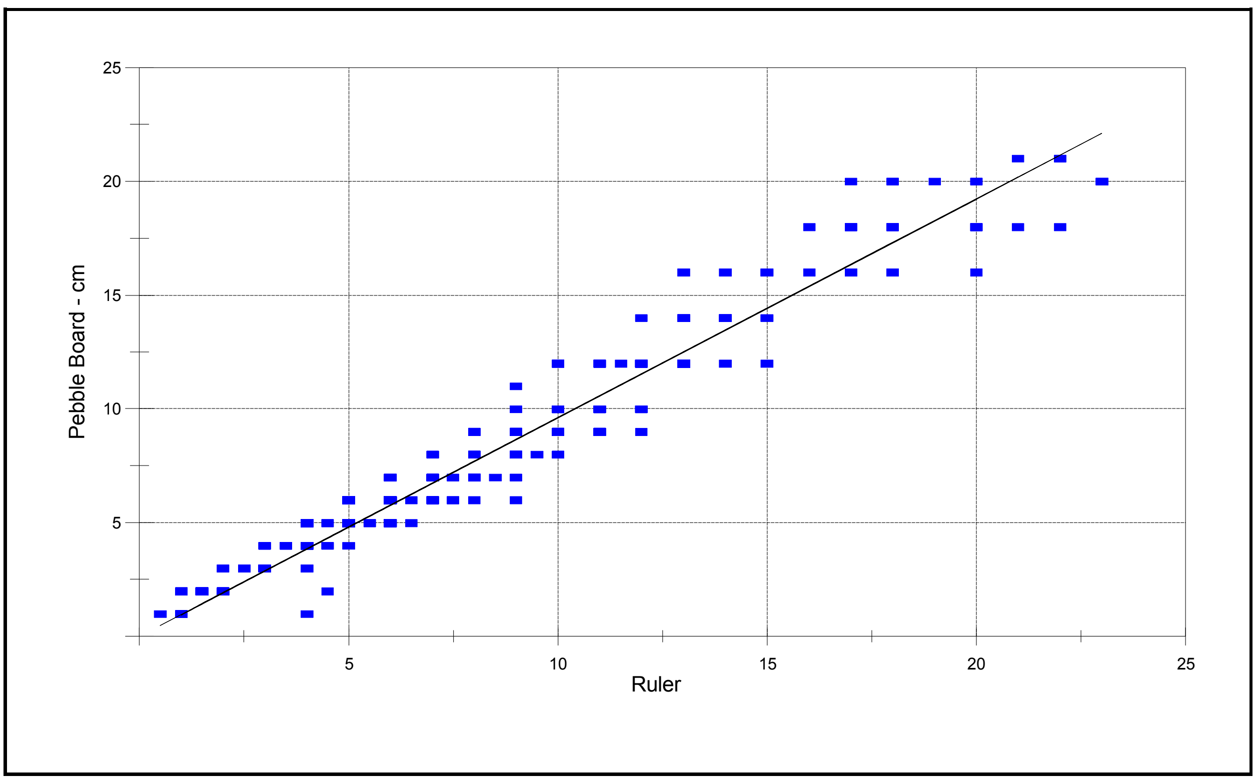

Figure 3.32. Comparison of cobble size measured with ruler and template and the resulting regression line.

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on one axis and the template measurement on the other, with a regression line (intercept = 0) also shown. The linear regression indicates that the diameters measured with the template are 96% of those measured with the ruler ($R^2 = .95$, $n = 460$, $p < .01$). No adjustment was made to prior year data, since the 4% difference is easily within measurement error. Standardizing the measurement method will help improve accuracy. Standardized methods and locations and adequate training of the samplers are critical.

Depth of Open Interstitial Space in Cobble Bars

Depths of open interstitial space for each of the bars sampled in 1995 appear in Table 3.27 along with a summary of the cobble and interstitial material. The comparative data from the 1994 sampling is also shown. The data are listed as actual depth in mm and depth expressed as the number of mean cobble diameters. Unfortunately, comparable data are not available from the Yampa spawning bar. Although specific requirements for spawning have not been determined, it is thought that depths less than 1.5 diameters are not likely to be adequate, with 2 diameters or more preferable. Based on this
criteria, sites below RM131.2 exhibit less suitable conditions than the sites above this location, even though the cobble size appears adequate.

Since 1995, open interstitial space has been surveyed at the four locations for which cobble size has been measured. A summary of the results appear in Table 3.28. Low runoff in 1996 and storm events near spawning in 1997 and 1998 have limited the open interstitial space during the after runoff samples. Most severely affected is the potential bar at RM 168.4. The least affected is the potential bar at RM 173.8.

Appendix A contains three-dimensional surface plots of depth of open interstitial space (depth to embeddedness) for these four locations. These plots show a 3-D surface plot of the top of the bar in the vicinity of the sampling with the depth of open interstitial space shown as 3-D “posts” at the location the measurement was taken.

Topographic Changes in Cobble Bars

Topographic surveys completed for three of the bars (173.7, 168.4 and 132) are shown in Appendix A. Figures are included for each bar showing a comparison of the bar topography for all surveys on one figure, the bar topography with open interstitial measurements on another set of drawings and surface plots of the change in the bars between surveys on a third set. The changes are summarized in Table 3.29 for each of the bars.

While the gross change in the bars (average elevation change) is small for all bars (#0.10 m), the pattern of change in response to flow is different among the bars. Only the bar at 132 was surveyed in 1995, showing an increase in bar elevation of 0.09 m. During 1996, RM 173.7 was depositional and the other two were slightly erosional. However the maximum and minimum elevations were reduced for all three bars. Between 1996 and 1997, RM 173.7 was erosional, although the maximum elevation increased. The other two bars were depositional. In 1998 all three bars were depositional.

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Table 3.27. Summary of cobble, open interstitial space and interstitial material for potential spawning bars in the San Juan River surveyed in 1995.

River Mile	Site	Cobble Size			Max. Depth of Clean Voids		Interstitial Sediment			Column Velocity		
		D84	D50	D16			D84	D50	D16	Mean	Max.	Min.
		mm	mm	mm	mm	Cobble Dia's.	mm	mm	mm	cm/sec	cm/sec	cm/sec
173.70		125	72	45	170	2.4	9.3	2.6	0.7	75	90	60
172.00		120	75	43	210	2.8	9.2	2.1	0.6	86	105	58
169.00		90	60	41	170	2.8	10.6	6.5	1.2	105	138	70
168.40		110	70	46	225	3.2	10.1	4.8	0.8	83	140	60
166.60	**San Juan Power Plant Diversion Dam**											
163.70	**Four Corners Power Plant Diversion Dam**											
163.00		123	90	55	200	2.2	10.1	5.1	0.8	111	138	90
158.80	**Hogback Diversion Dam**											
142.00	**Cudei Diversion Dam**											
137.70		105	70	45	230	3.3	10.0	4.6	0.8	75	90	60
137.30		145	90	58	150	1.7	8.0	1.2	0.4	82	90	75
132.00	Main Bar	95	58	32	240	4.1	9.5	3.0	0.3	100	128	67
131.20	Red Wash	75	47	24	130	2.8	9.8	4.0	0.4	58	110	22
131.20	Main	63	41	21	130	3.1	9.4	2.8	0.4	66	95	32
109.80		130	80	49	105	1.3	9.5	2.4	0.6	74	80	67
88.00		104	82	53	90	1.1	10.6	6.5	1.0	63	68	58
82.95	C	78	61	42	115	1.9	9.5	3.4	0.6	77	90	65
82.90	B	158	112	65	85	0.8	9.0	1.6	0.5	77	90	70
82.85	A	90	59	40	80	1.4	3.5	1.2	0.6	113	130	90
78.00		130	89	71	115	1.3	9.7	3.8	0.7	68	82	45
76.60		124	101	71	100	1.0	7.1	1.3	0.6	72	90	55
Average		106	71	45	150	2.1	9.4	2.7	0.5	81	103	61
Yampa Tertiary		110	76	46								
132	94 Bar	100	65	46	450	6.9						
131	94 RW	62	35	21	120	3.4						
131	94 Main	80	45	25	170	3.8						
131	93 RW				120							
132	93 Bar				120							

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Table 3.28. Summary of depth of open interstitial space in cobble bars.

DEPTH EXCEEDENCE	1993	1994	1995	1996	1997[1]	1998[6]
	Areal extent exceeding stated depth of open interstitial space - m^2					
RM 173.7(potential spawning bar), cobble D50 = 5 cm						
1 x D_{50}	n/a	n/a	362[2]	2204 / 3437[3]	1356	3499
1.5 x $D5_{50}$	n/a	n/a	342[2]	1512 / 1868[3]	571	1913
2.0 x D_{50}	n/a	n/a	321[2]	907 / 822[3]	214	656
RM 168.4 (potential spawning bar), cobble D50 = 6 cm						
1 x D_{50}	n/a	n/a	495[7]	566/857	374	2238
1.5 x $D5_{50}$	n/a	n/a	262[7]	170/171	94	767
2.0 x D_{50}	n/a	n/a	111[7]	57/86	94	64
RM 132 (main spawning bar), cobble D50 = 6 cm						
1 x D_{50}	64[4]	126[4]	853	712	688 (367)[5]	309
1.5 x D_{50}	10[4]	63[4]	500	522	276(67)[5]	148
2.0 x D_{50}	2[4]	29[4]	317	308	172(33)[5]	40
RM 131 (lower red wash spawning bar), cobble D50 = 5 cm						
1 x D_{50}	n/a	466	222	66	157	123
1.5 x D_{50}	n/a	106	100	66	105	46
2.0 x D_{50}	n/a	29	47	33	66	15

[1] A large storm event occurred between July 29 and August 14, peaking twice in the 6,000 cfs range. This storm was just prior to survey in 1997, which appears to have partially filled some open interstitial space with sediment.
[2] The area surveyed was limited to chute channels (362 m^2) compared to full bar (8,000 m^2) in 1996 and 1997.
[3] The first value is pre-runoff, the second post-runoff
[4] The area surveyed was about 10% that of later years, but was concentrated in the cleanest areas.
[5] First value is estimated based on a 20% subset survey taken in July prior to the storm event. Value in parenthesis was taken just after the storm event.
[6] A sediment laden storm occurred between July 27 and Aug 5 (Peak 2500 cfs), just prior to Survey
[7] The area surveyed was limited to chute channels (774 m^2) compared to full bar (9,000, 11,300, 7,800 m^2) in 1996,1997, 1998, respectively).

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Table 3.29. Summary of changes in three cobble bars in the San Juan River surveyed between 1995 and 1998. (needs to be converted to metric).

Survey Date	Average Elev. (M)	Change in Elev. (ft)	Max Elev. (ft)	Min Elev. (ft)	Ac-ft SJ@ Farmington	Max cfs
Bar at RM 173.7						
04/02/96	100.00		94.8	89.0		
07/08/96	100.12	0.12	94.5	89.5	327,207	3550
08/22/97	99.78	-0.34	95.0	87.8	1,708,389	12,400
08/10/98	99.88	0.10	94.8	87.6	1,322,083	7,580
Bar at RM 168.4						
04/03/96	100.00		95.15	91.46		
07/09/96	99.97	-0.03	95.12	90.10	326,000	3,550
08/22/97	100.05	0.08	95.11	91.60	1,705,000	12,400
07/29/98	100.19	0.14	95.49	91.35	1,360,000	7,580
Bar at RM 132						
03/08/95	100.00		94.26	88.30		
07/25/95	100.28	0.28	94.49	89.19	1,478,000	11,700
03/13/96	100.25	-0.03	94.09	88.73	478,000	2,550
7/10/96	100.20	-0.05	93.66	88.59	355,000	3,550
8/21/97	100.55	0.35	93.56	87.79	1,700,000	12,400
8/11/98	100.68	0.13	94.07	88.79	1,330,000	7,580

Examination of topographic surface plots in Appendix A point out more significant differences than the gross changes would suggest. The shape of the bar at RM 173.7 shows only minor change, most of which is concentrated around the chute channel. This is also the location of the deepest open interstitial space. The bar at RM 168.4 demonstrates more broadly distributed, but small change, although a small chute channel is beginning to develop through the bar. The bar at RM 132 is more dynamic. The changes in certain locations of the bar have been large and the shape and size of the chute channel have both changed substantially over the survey period.

From the detailed surveys of these bars, and data collected at other suspected spawning sites that have since been lost due to channel change, it is obvious that any given spawning bar will only have utility for a finite period of time. For example, the bar in the Red Wash secondary channel at RM 131.2 where Miller (2000) documented Colorado pikeminnow in spawning behavior in 1994 was created in 1993 and isolated again by 1996. As the characteristics of a bar change and the features required for spawning lost, other bars develop. For the period of this survey (1995 - 1998), the three bars surveyed have maintained conditions thought to be necessary for spawning and will likely continue for some time. Among these, it appears that the upstream bars are more stable than the RM 132 bar and will likely persist longer. The dynamic nature of the bars is expected and necessary to maintain areas of open interstitial space.

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Cobble Bar Survey Summary

Based the analyses in this section, it appears that sites with suitability equal to those used by Colorado pikeminnow exist upstream of the suspected sites(geomorphological and habitat suitability does not necessarily equate to use, but indicates potential). If these upstream sites could be used for spawning, the backwater habitat available downstream from spawning would increase in area by 33-43% and in number by 30-35%. In addition, the distance between spawning site and Lake Powell would be increased by up to 31% or 45 miles.

Cobble Transport Analysis

The range of values for three predicted conditions of cobble movement (initiation of motion, average motion, full motion) appears in Table 3.30 for the modeled reaches. The flows at which the three conditions are met in each modeling reach are shown in Table 3.31.

Table 3.30. Boundary shear stress conditions at various flow rates for four modeled reaches.

	CFS	RM 133.0		RM 167.0		RM 169.0		RM 173.7	
D_{50} - cm			*5.00*		*6.00*		*6.00*		*4.00*
Required for beginning motion (J^*_c= 0.02 - 0.03)		**0.34 - 0.51**		**0.41 - 0.61**		**0.41 - 0.61**		**0.27 - 0.41**	
Required for average motion (J^*_c= 0.03 - 0.045)		***0.51 - 0.76***		***0.61 - 0.91***		***0.61 - 0.91***		***0.41 - 0.61***	
Required for full motion (J^*_c= 0.45 - 0.06)		***0.76 - 1.01***		***0.91 - 1.22***		***0.91 - 1.22***		***0.61 - 0.77***	
				Boundary Shear Stress					
	1,000		0.07		0.12		0.07		0.11
	2,000		0.12		0.17		0.17		0.17
	3,000		0.18		0.24		0.25		0.23
	4,000		0.24		0.30		0.31	**0.28**	0.28
	5,000		0.29		0.35		0.36	**0.34**	0.34
	6,000	**0.34**	0.34		0.40	**0.42**	0.42	**0.38**	**0.38**
	7,000	**0.41**	0.41	**0.48**	0.48	**0.46**	0.46	***0.44***	**0.44**
	8,000	**0.47**	0.47	**0.53**	0.53	**0.51**	0.51	***0.48***	**0.48**
	9,000	***0.52***	**0.52**	**0.58**	0.58	**0.56**	0.56	***0.53***	**0.53**
	10,000	***0.59***	**0.59**	***0.65***	**0.65**	***0.61***	**0.61**	***0.57***	0.57
	11,000	***0.63***	**0.63**	***0.71***	**0.71**	***0.66***	**0.66**	**0.61**	***0.61***
	12,000	***0.67***	**0.67**	***0.78***	**0.78**	***0.71***	**0.71**	**0.65**	***0.65***

Note: **Bold = beginning motion**
Bold italics = average motion
Shadowed cells = full motion

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Table 3.31. Flows required to meet critical shear stress conditions for cobble transport.

Modeling Reach	133	167	169	173.7
Minimum Channel Capacity - cfs	7,500	7,100	7,100	10,000
Average Channel Capacity - cfs	8,000	8,000	8,500	10,500
Cobble D_{50} - cm	5.0	6.0	6.0	4.0
Minimum flow for beginning motion - cfs	6-8,000	4-6,000	4-9,000	3-7,000
Ave flow for beginning motion - cfs	6-9,000	7-10,000	6-10,000	4-7,000
Minimum flow for ave. motion - cfs	8-12,000	6-10,000	9->12,000	7-10,000
Ave flow for ave. motion - cfs	9->12,000	10->12,000	10->12,000	7-11,000

Note: Flows above bankfull are not modeled accurately because of the inability to accurately assess the roughness of the overbank condition or define the flow channel without large amounts of additional data and the ability to calibrate the model at these higher flows. Therefore, values above bankfull presented in the table are qualitative only.

According to these calculations, all of the modeled reaches have boundary shear stresses in the range necessary for incipient motion for the average of all cross-sections at or below bankfull flow. Only one reach attained the condition (J^*_{c50} = 0.030 to 0.045) that the literature discussed in the **METHODS** section would suggest is necessary for measurable transport on average, although in all but one reach some transects were predicted to reach the condition below bankfull flow. The comparison of pre- and post-runoff surveys of the upstream cobble bar at RM 173.7 shows an increase in mean bar elevation during the 1996 runoff period and a subsequent decrease in average elevation during the 1997 runoff period. This would suggest that cobble was transported to the bar at a flow of less than 4,000 cfs (1996) and eroded from the bar during the higher flows in 1997. The bar at RM 168.4 was stable in 1996 but aggraded slightly in 1997. Given the morphological nature of the changes in the examined cobble bars, any noted cobble transport could have resulted from local scour and deposition rather than from immigration or emigration of material, but the change in the bars could have resulted from upstream transport based on the assumption of the low end of required J^*_{c50}. Based on these findings, the conditions for cobble transport in these reaches range from marginal to plausible at or below bankfull discharge, depending on the reach. However, adequate conditions exist for marginal transport only if the smaller J^*_{c50} values are applicable.

Three possible conditions found in the San Juan River supply some possible explanations for predicted transport to be somewhat less than anticipated. First, cobble diameter measurements erred on the large side; second, incipient and average motion begin at lower dimensionless shear stress values (low end of the range) in the San Juan River; and third, cobble is not adequately transported through lower gradient reaches of the system.

While the first condition is verified by the accuracy of measurement versus the diameter found using the template, samples taken in 1998 actually suggest that the mean cobble diameter may be a bit

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larger than the earlier measurements show. It is still possible that the samples have an inherent bias to larger particles , especially due to the underwater nature of the sampling. However, it appears that this is not a valid explanation for predicted transport appearing less than anticipated based on field observation.

The second condition may be because cobble shape and the presence of sand in the system influence cobble transport. If the sand acts as a lubricant, then transport could begin at lower average values. The typical process of bar formation observed in the San Juan River consists of erosion of an upstream bar under high-gradient conditions across the bar and subsequent deposition on a bar located downstream. In addition, boundary shear stress may vary locally with varying substrate, depth, and velocity. As such, cobbles in a high-gradient reach may experience an adequate boundary shear stress for saltation or entrainment. The abundance of sand in the San Juan River may facilitate continued transport once a cobble is dislodged from the bed. This condition would tend to support using the lower end of the J^*_{c50} values.

The third condition is that cobble becomes locally available and transported from shoreline sources or that bar erosion allows short-distance movement, even though system shear stress is not adequate to move cobble through long, low-gradient reaches from upstream sources. In such a case, cobble transport is adequate in the short-term to locally maintain currently active cobble bars, and long-term sediment balance is met by continuous upstream erosion (head cutting) and subsequent downstream deposition to the extent that the higher gradient locations move through low-gradient reaches. This phenomenon, along with the formation of new secondary channels and resulting rapid, short-term transport, has been observed locally in the San Juan River. Further, local imbalance has caused deposition and subsequent change in main or secondary channel location. Such activities maintain sediment balance in the system over the long term, but may cause local imbalance.

Since the empirical data indicate cobble movement, even at low flows, and show that cobble movement generally increases with increased flow magnitude and duration, it is quite possible that some combination of the last two conditions exist in the San Juan River. Cobble bars will continue to be monitored for changes with varying flow conditions.

The model studies indicate that flows in the neighborhood of channel capacity (8,000 cfs) are necessary to transport cobble of sufficient size and quantity to build bars. While effective flow, in terms of total sediment transport and channel maintenance, is typically lower than bankfull flow (Andrews 1980, Pitlick and Van Steeter 1998), the bankfull flow recommendation is for cobble transport and bar formation, and it is needed less frequently than typical effective flows. Sediment transport theory, as applied to four modeling reaches, does not support a recommendation less than bankfull for the required cobble transport, and flows above bankfull provide very little additional shear stress for the volume of water required because of large overbank flow. Therefore, bankfull flow is the recommended flow magnitude to support cobble transport in the San Juan River.

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Low Velocity Habitat Creation and Maintenance

Cobble/Sand Bar Monitoring

D-1: The results of 5 surveys of the bar located downstream of transect D-1 at RM 88 are summarized in Table 3.32. Three-dimensional surface plots of the survey areas are shown in Appendix B. The bar complex was subdivided to define points that would be in the backwater area separately from the remainder of the bar. Both minimum and maximum elevations are shown for the entire bar and for the backwater area and average elevations are shown for the entire area surveyed.

By comparing the various average and maximum elevations for the backwater area and the entire survey area, a definite pattern emerges. The backwater area filled somewhat during the summer after runoff and scoured over winter, while the bar remained about constant in elevation and shape. During spring runoff in 1995, the bar was scoured, losing about 0.6 m in maximum elevation and 0.15 m in average elevation. The upper end of the bar was eroded away on the main channel side and the lower end of the bar is nearly gone.

Based on this series of surveys, the bar appeared to be in an erosional state during the 1995 runoff (peak discharge 329 m^3/sec (11,600 cfs) at Four Corners), losing substantial area and elevation. The backwater area accumulated some sediment during the summer low-flow period and was cleaned some during the winter flow period, with little change during peak runoff. During the August 14 and October 12, 1995 surveys, no backwater existed at 41 m^3/sec (1,450 cfs) and 25.5 m^3/sec (900 cfs), respectively.

Table 3.32. D-1 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Cobble Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 24, 1994	94.5	91.4	96.6	91.4	93.40
October 7, 1994	94.3	92.0	96.7	92.0	93.45
March 5, 1995	94.3	91.5	96.6	91.5	93.32
August 14, 1995	93.2	91.2	94.7	90.9	92.83
October 12, 1995	93.2	91.3	94.7	90.8	92.89
March 11, 1996	93.1	91.3	94.6	90.8	92.59
July 19, 1996	93.8	91.4	94.6	90.9	92.68
October 8, 1996	94.3	91.2	94.7	90.9	92.79

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By 1996, the bar that formed the backwater is nearly eroded away. The backwater is essentially gone by October 1996. Surveys were terminated at the end of 1996.

D-4: The results of 5 surveys of the bar located at transect D-4 (RM 86.4) are summarized in Table 3.33 Three-dimensional surface plots of the survey areas are shown Appendix B. The bar complex was subdivided as described above. At this location, the minimum elevation of the backwater area increased during the summer of 1994, decreased during the winter, changed very little in depth during the spring runoff in 1995 but increased in extent and then decreased again during the summer of 1995. The maximum elevation of the entire bar changed very little, with a slight increase shown during spring runoff and a decrease shown in summer 1995. It is apparent that the bar is being eroded during spring runoff on the main channel side. Even though the maximum elevation increased during spring runoff, the bulk of the bar controlling the backwater did not change in elevation relative to the post runoff condition in 1994, although the shape changed considerably. Backwater conditions exist at flows above about 900 cfs and becomes a flow-through at flows above about 1,500 cfs. Below 900 cfs, the berm that forms at the lower end of the backwater isolates water in the backwater area from the main channel. The berm appears to develop during the summer and is eroded during spring runoff.

This bar is also erosional on its main channel margin and relatively stable along the top. The higher flows during 1995 did not increase the elevation of the top of the bar, but did cause additional erosion on the margin. The 1996 flows induced further margin erosion. If the trend continues, the backwater will be lost. Surveys were terminated at the end of 1996.

Table 3.33. D-4 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Cobble Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 24, 1994	94.4	93.3	98.2	92.8	95.54
October 7, 1994	94.7	93.9	98.3	93.4	95.85
March 5, 1995	95.0	93.5	98.2	91.8	95.74
August 14, 1995	94.6	93.3	98.4	92.2	95.41
October 12, 1995	94.2	92.5	98.0	91.8	95.47
March 11, 1996	94.6	93.1	98.4	92.3	95.34
July 19, 1996	95.2	93.2	97.3	92.5	95.42
October 8, 1996	95.3	93.9	98.2	92	95.58

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CH-2: The results of 5 surveys of the bar located at transect CH-2 (RM4) are summarized in Table 3.34. Three-dimensional surface plots of the survey areas are shown in Appendix B. The bar complex was subdivided as described above. This is a very dynamic site with both deposition and scour occurring continually along the margins of the thalweg and over the entire area at higher flows. The values in Table 3.34 are not as instructive as for the other two bars due to the dynamic nature of this site. However, by inspection of the data for the entire bar, it is evident that the higher flows during 1995 runoff (both volume and magnitude) did not increase the elevation of the bar. If fact, the maximum elevation of the bar decreased by 0.2 ft during this time and actually increased during 1995 summer flow to return to the maximum elevation recorded in 1994. On average, the elevation of the entire area surveyed dropped by 0.06 ft during spring runoff and increased by 0.32 ft during the summer of 1995. The minimum elevation of the bar occurred at the end of the 1995 runoff, demonstrating scour of nearly 3.0 ft. However, this is at a location on the margin of the thalweg that occurred as the thalweg shifted.

During the period of August 25, 1994 to October 12, 1995, the thalweg shifted from river left at the lower end to river right and then back to river left. At the upper end it shifted from river right to river left. The large but shallow backwater that existed in 1994 disappeared in 1995. After runoff in 1995 no backwaters existed in this reach at flows above 25.5 m^3/sec (900 cfs). In fact, at flows of 38 m^3/sec (1,350 cfs), nearly the entire area is under water.

Table 3.34. CH-2 Bar Survey Summary.

Date of Survey	Backwater Area Only		Entire Sand Bar		
	Max Elev	Min Elev	Max Elev	Min Elev	Ave Elev
August 25, 1994	93.0	91.5	94.4	90.3	92.18
October 6, 1994	94.0	91.3	94.3	90.4	92.24
March 4, 1995	93.2	90.0	94.1	89.9	92.23
August 15, 1995	93.3	92.6	94.1	87.1	92.31
October 13, 1995	93.8	92.8	94.4	90.1	92.66
March 8, 1996	93.6	91.7	94.2	90.8	92.55
July 18, 1996	94.1	90.6	94.1	89.3	92.30
October 9, 1996	94.4	89.4	94.7	89.4	92.60
March 12, 1997			94.6		92.41
August 20, 1997			95.5		93.11
September 9, 1998			96.7		95.10

This trend of continuous local change in bar shape but no change in average or maximum bar elevation continued until 1997. From March 1997 until September 1998, the average elevation of the bar increased by 0.76 m and the maximum elevation increased by 0.61 m, similar to the change in the C-2 transect discussed earlier. This change is in response to the rising Lake Powell surface elevation.

Summary: Between 1994 and 1996, none of the bar heights responded to differences in runoff. It appears that the bars at D-1 and D-4, and their associated backwaters, formed as alluvial material deposited during earlier times eroded away, exposing a more resistant cobble bar with a backwater behind the bar. At flows in the range of 283 to 340 m^3/sec (10,000 to 12,000 cfs) the bars are eroding. At 100 m^3/sec (3,540 cfs) there was no obvious erosion. They may erode over a larger range of flows, but flows higher than 12,000 or between 10,000 and 3,540 cfs have not been tested. These are not permanently maintained features, but are representative of the many transitory backwaters in the system.

The conditions at CH-2 are much different. The sands forming the bars at this location are deposited in response to the gradient change created by Lake Powell backwater. In 1995 a backwater condition (elevated Lake Powell water surface created higher water surface elevation at a given flow in this reach) existed, yet the bar did not build in elevation during spring runoff. However, this backwater condition did not occur until the end of runoff, with no effect this far up river. In 1996, the water surface elevation again dropped. The lack of average elevation change would indicate that sediment transport was about in balance (no scour or deposition) at this site through 1996. Beginning in 1997, in response to lake elevations, the bar began to rise and continued through 1998, in response to Lake Powell water surface elevations.

Maintenance of Secondary Channel Associated Backwaters

Based on six measurements over a range of discharges, a relationship was developed to predict secondary channel discharge as a function of main channel flow. The relationships developed for each channel had an r^2 of 0.99 (p=0.002). The plots of the mean depth of the backwaters and the main and secondary channel hydrographs are shown in Figure 3.33. Suspended sediment concentration was measured about twice weekly during this time to provide data for later modeling.

HEC-6 was used to model sediment transport in the two secondary channels so that predictions could be made for other conditions. Survey data from May 13 and 19, 1997, were used for channel morphology in the model. Manning's *n* was determined using HEC-RAS, by varying Manning's *n* until the modeled water surfaces matched the surveyed water surfaces. This resulted in a Manning's *n* of 0.023 for Sand Island and 0.027 for Montezuma Creek. These *n* values are on the low end of the range for typical, natural channels, but they are consistent with the predominantly smooth-bottomed, relatively straight secondaries being modeled. Between May 13 and August 9, 1997 (the runoff period modeled), eight of the ten total surveys were completed in each secondary. To calibrate HEC-6, the hydrographs in Figure 3.33, with their accompanying sediment load, were routed through the channels. Parameters were adjusted until the modeled volumetric change in

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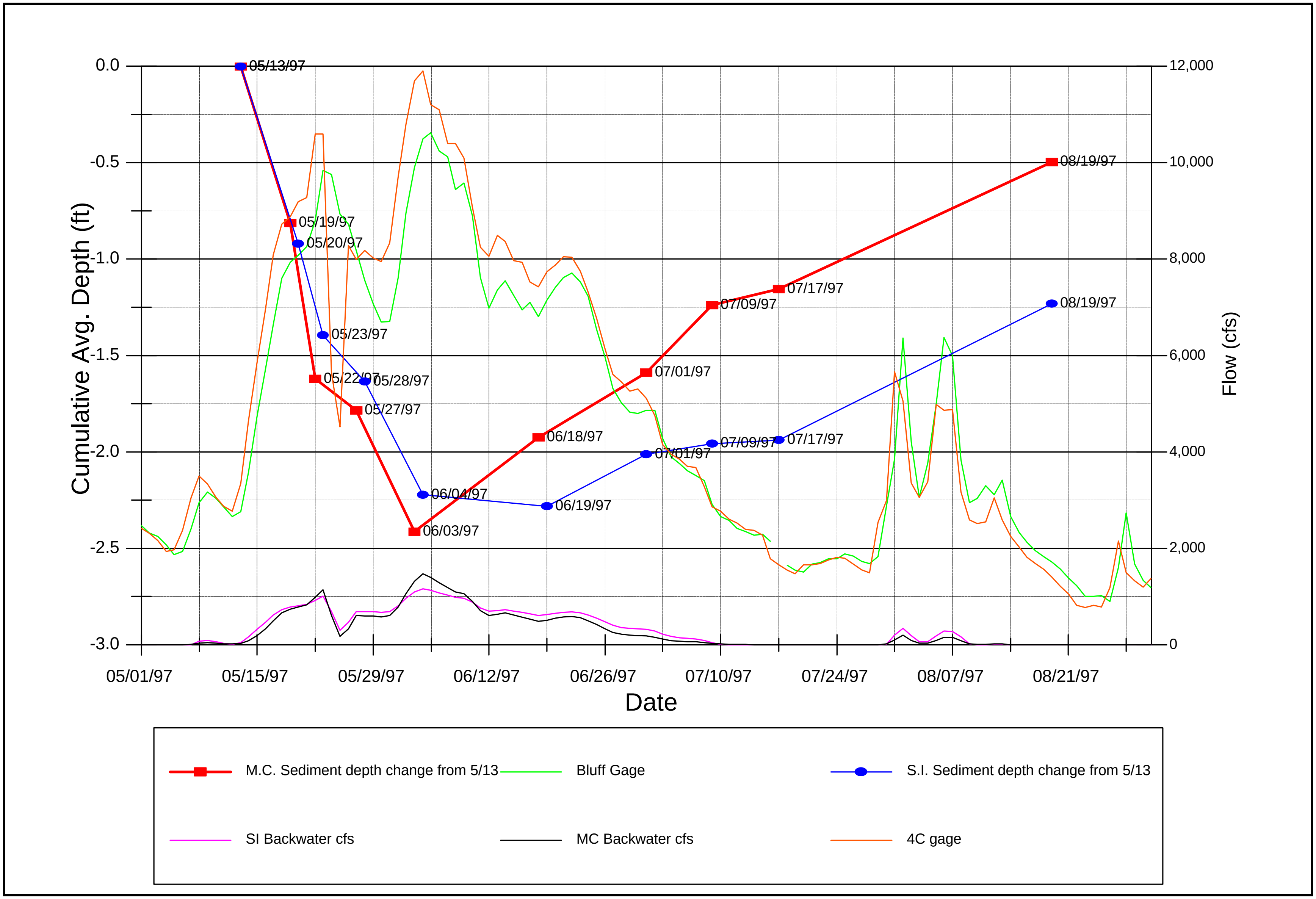

Figure 3.33. Flow and backwater depths for 1997 runoff for the Montezuma Creek and Sand Island sites.

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sediment load matched as closely as possible the measured volumetric change in sediment load. The parameter adjusted was the size distribution of inflowing suspended sediment. For Sand Island, there was one sediment size distribution for the entire time period, which was 50% very fine sand and 50% fine sand. For Montezuma Creek, the starting sediment size distribution was 71% very fine sand and 29% fine sand, which changed to 99% medium sand and 1% coarse sand on May 25, 1997. Suspended sediment size fractionation was completed to determine composition of sand and silt, not for a range of fine substrate sizes, so some calibration was necessary. Figure 3.34 shows the measured and modeled results for the two backwaters.

For these secondary channels, the HEC-6 results for sediment inflow and outflow were extremely sensitive to even small changes in the sediment size distribution. For example, starting Montezuma Creek with 75% very fine sand and 25% fine sand instead of 71% very fine sand and 29% fine sand gave the results shown in Figure 3.35. Furthermore, the scatter in the fit in the early part of the runoff period indicated sensitivity to sediment concentration as well as particle size. The scatter about the mean was because of changes in sediment concentration at the break points. Further, one dimensional modeling of these complex processes limits the robustness of the analysis. Therefore, without a more-detailed particle size distribution and daily sediment concentration, projecting these results for other flow and sediment conditions is qualitative, at best.

Using the calibrated parameters, model runs were completed for 1993 and 1995 with sediment concentrations collected during those years at about 10-day to 2-week intervals. During both years, backwaters were well maintained by flows after runoff. At the end of the runoff in 1993, sediment concentration was at its lowest point of the 2 years. The model was also operated for 5 years of simulated hydrographs from river operations model output to represent five different hydrograph scenarios and four sediment concentrations. The sediment concentration patterns used represented a low-sediment concentration year similar to 1993 at Shiprock and Montezuma Creek, representing upstream and downstream differences, and a relatively high concentration pattern. These patterns were chosen to demonstrate the differences in years and reflect the normal upstream-to-downstream gain in sediment. The concentrations used are shown in Table 3.35. Disregarding storm peaks, they represent the range of expected concentrations during spring runoff in the San Juan River. The results of the modeling runs are summarized in Table 3.36. Results are shown only for Montezuma Creek. Sand Island results are similar, except the volume of removed sediment is less because the backwater was smaller. Maintenance was characterized as excellent, good, fair, or poor. Because results of the two low and two high sediment concentrations were similar, a qualitative evaluation was indicated for the two main categories only, not for the upstream or downstream conditions. In nearly all cases, the backwater was maintained at maximum depth during the runoff period, usually by peak flow conditions, and then partial refilling occurred on the descending limb. While flushing usually began at flows lower than 5,000 cfs, it became more effective at higher flows; therefore, 5,000 cfs is used as the threshold condition for effective flushing. While duration required for cleaning varies depending on the shape of the hydrograph and suspended sediment load, 3 weeks at flows above 5,000 cfs is set as the minimum condition for full cleaning as an average condition, assuming that the flow follows a typical increasing and decreasing pattern to allow for flows above 5,000 cfs for the cleaning period.

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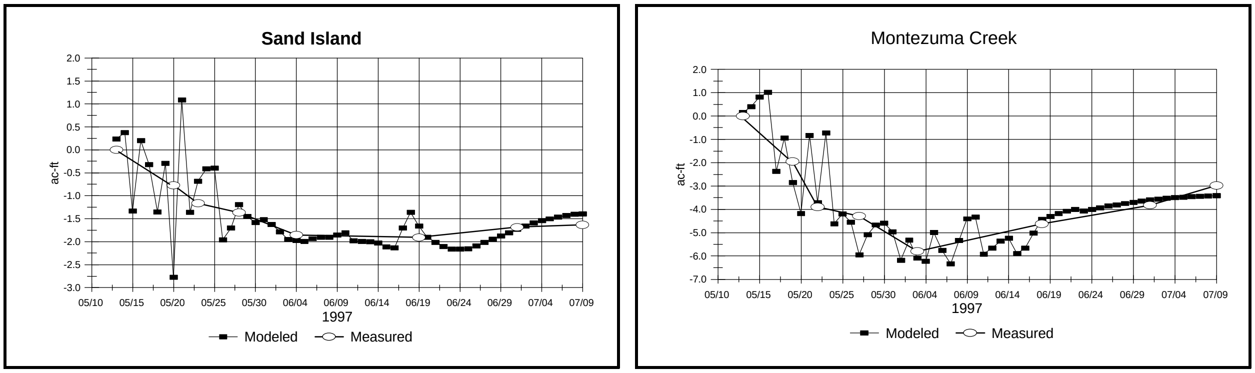

.**Figure 3.34. HEC-6 calibration results for Sand Island and Montezuma Creek.**

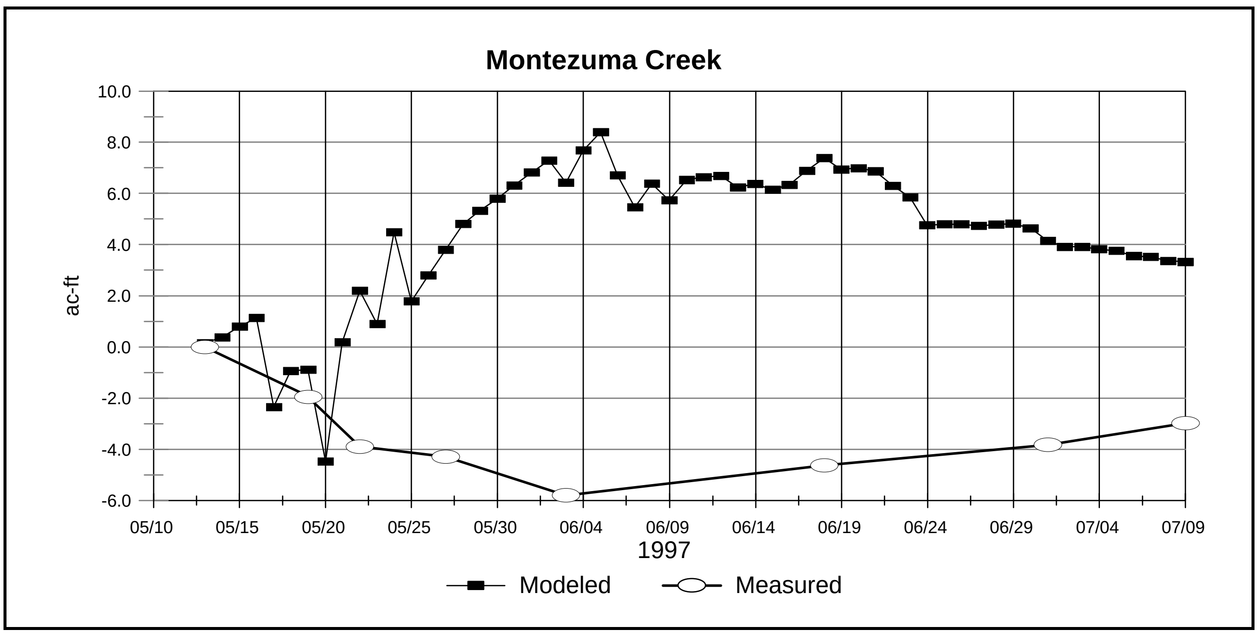

Figure 3.35. Modeling results with small change in grain size to demonstrate sensitivity.

From the empirical survey data and modeled results, several preliminary conclusions can be made: (1) main channel flows above 4,000 cfs initiate flushing, but effective flushing occurs at about 5,000 cfs, (2) if flows do not exceed 5,000 cfs, more time is required for adequate flushing, (3) shorter descending limb duration results in less refilling and better maintained backwaters after runoff, (4) short duration, steep ascending limbs to relatively high peaks (approximately 9,000 to 10,000 cfs), combined with steep descending limbs, maximize backwater maintenance for the volume of water required compared with more-extended runoff with lower peaks.

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Table 3.35. Sediment concentrations (parts per million (ppm)) used in HEC-6 simulations.

	Low		High	
	Upstream	Downstream	Upstream	Downstream
	190	300	550	800
May 17 - May 31 - ppm	275	415	750	1,050
May 31 - June 10 - ppm	170	450	1,050	1,300
June 10 - June 20 - ppm	110	170	400	460
June 20 - June 27 - ppm	70	130	150	200
June 27 - July 31 - ppm	20	30	150	100

Table 3.36. Summary of HEC-6 modeling results for Montezuma Creek site.

	1997	1995	1993	1976	1970	1960	1937	1930
Nose - weeks	4	0	10	0	0	0	6	0
Ascending limb - weeks	4	10	4	5	2	4	2	4
Descending limb - weeks	4	5	4	2	6	1	6	4
Peak flow - cfs	11,900	12,000	10,000	8,900	8,800	9,500	9,200	10,000
Begin cleaning flow - cfs	4,500	4,000	4,000	3,800	3,800	3,900	4,600	4,000
Weeks to maximum cleaning	3	5	10	2	2	2	3	2.5
Results - low concentration	n/a	n/a	n/a	good	good	excell.	good	good
Results - high concentration	n/a	n/a	n/a	poor	poor	excell.	fair	poor
Results - actual concentration	good	good	good	n/a	n/a	n/a	n/a	n/a
Sediment concentration	mod.	low	low	n/a	n/a	n/a	n/a	n/a

It is important to note that location in the system may influence the effectiveness of backwater-maintenance flows. The backwaters measured and modeled in this discussion are located in Reach 3 and are subject to heavy sediment inflow. Backwaters higher in the system may clean faster because they receive less sediment inflow. In 1998, two additional backwaters will be modeled in Reach 5 to assess any difference in site locale. Also, additional calibration data will be collected to refine the modeling process. As with other flow recommendations, additional monitoring is required, and future modification may be warranted.

Channel Morphology Response Summary

During the 7-year research flow period, channel cross-section surveys indicated a slight increase in channel depth and channel capacity in response to the increase in spring runoff volume and magnitude, regaining some of the cross-sectional area lost after closure of Navajo Dam. Bankfull capacity in Reaches 3 to 6 (below Farmington, New Mexico) may have increased by as much as

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12%. Most of this change occurred by 1995, with relative stability since that time. Most of this increase in channel capacity is a result of removal of sand from the streambed. Relatively little net cobble loss (about 10% of the total loss) has occurred. There has been no appreciable change in channel complexity as measured by the number of islands present at base flow as a result of the research flows, although channel complexity did increase after flows exceeded 10,000 cfs for 11 days in 1995.

At some locations, cobble transport occurs at flows as low as 2,500 cfs. Cobble movement to and from cross-sections generally increased with increased flows, but movement is not highly correlated to any single hydrologic parameter. A combination of hydrologic conditions, including peak flow magnitude and days above 10,000, 8,000, 5,000, and 2,500 cfs, explains about 70% of the variation in scour and deposition of cobble at the cross-sections, although the correlation is not statistically significant at the 95% level because of the limited degrees of freedom.

Bankfull channel capacity below Farmington is about 8,000 cfs, with some overbank flows as lows as 7,100 cfs. Cobble transport modeling in the San Juan River only marginally supports observed cobble transport, but given the approximations in modeling and potential measurement error, there is not large disagreement between observed and modeled conditions. Based on the combination of the modeling results and measurement of cobble movement, flows above 8,000 cfs for a minimum of 8 days are likely necessary for reconstruction or replacement of cobble bars in the system. Flows of about 2,500 cfs for 10 days or more are adequate to develop clean cobble for spawning and should be provided regularly (at least once every two years). Bars erode slowly, so flows above 8,000 cfs are needed less regularly than the smaller reshaping flows. For channel maintenance purposes, flows should exceed 8,000 cfs for 8 days with an average frequency of 1 year in 3 years. Periodic flows above 10,000 cfs are helpful in maintaining channel complexity, providing new cobble sources for subsequent bar construction, and maintaining floodplain integrity. Frequency of these flows is less critical than that of maintenance flows, and a lower frequency is desirable if it will allow greater effectiveness of high flows. A duration of 5 days with an average recurrence frequency of 1 year in 5 years is suggested by the empirical data and is consistent with mimicry of a natural hydrograph when considering the historical loss of channel capacity. Periods of high flow following low-flow years are important to the maintenance of the geomorphology of the system.

Kondolf and Wilcock (1996) suggested that providing channel maintenance flows of magnitudes that transport both sand and gravel may not achieve the objective of reducing the sand content of the bed and may result in loss of coarse sediment from the system. Analysis of the data for the San Juan River does not indicate either condition as a problem with the flows recommended. Percent cobble substrate has increased with time, cobble is abundant in the system, the cobble bars surveyed do not appear to be degrading, and open interstitial space is consistently maintained. Transport conditions necessary to remove fine sediment from the system occur for much longer durations and at greater frequency than those required to transport cobble. Supplying cobble mobilization flows 1 year in 3 years is only a slight increase from post-dam conditions, a period that indicated a slight loss of channel capacity. While it is not likely that the concern suggested by Kondolf and Wilcock (1996) is a problem in the San Juan River, continued monitoring will be required to identify if a problem occurs and to adjust flow recommendations accordingly.

Backwaters in the San Juan River typically flush at flows above 4,000 to 5,000 cfs. When limited flow is available, the most-effective hydrograph scenario is one of a rapid ascending limb to a relatively high magnitude peak, followed by a rapid descending limb. For full flushing of backwaters, flows should be maintained above 5,000 cfs for 3 weeks or more, assuming a relatively natural hydrograph with a peak of 1.5 to 2.5 times this level. If flows are maintained at or near 5,000 cfs, substantially longer times are needed for flushing. While backwaters are not totally lost when flushing flows are inadequate, they are diminished in size and quality. Frequency of achieving flushing conditions will be influenced by the level of sediment accumulation in the prior years and the availability of water to achieve peak flows above 5,000 cfs for 3 weeks. Peaks between about 3,000 and 4,000 cfs may actually increase the filling of backwaters during runoff and should be avoided if possible.

While the flow conditions discussed here are based upon the response of the geomorphology, they form the basis of natural hydrograph mimicry, a condition that is desirable in restoration of habitat for native fishes (see discussion in Chapter 1). Application of the rates, durations, and frequencies represented here provides for a hydrograph shape and annual variability that is similar to natural conditions.

Suspended Sediment Sampling

Sampling Results

The suspended sediment concentrations at Farmington, Shiprock, Four Corners and Montezuma Creek sampling sites are plotted against discharge on Figures 3.36 through 3.39, respectively, for the 1992-1998 sampling period. Utilizing this full data set for each of these gages demonstrates the poor correlation between suspended sediment concentration and discharge for the San Juan River. These data were also plotted with the 1963-1980 daily data for the San Juan River near Bluff (located at Mexican Hat) in Figure 3.40 (no spot samples included).

Variability and range of sediment concentration from these data sets are similar to the historic data, although the average is in the low side of the historic range. Since the sampling design was to avoid storm events, the shift to the low side of the historic data is expected. When including the spot data that includes storm influenced concentrations, the ranges more closely match. The data do not suggest a shift in sediment concentration since 1980.

In an attempt to develop a sediment-discharge rating curve for the San Juan River, to assess the sediment transport capacity, an attempt was made to filter out any storm influenced data from the full data set. In filtering these samples, any sample that was considered to be influenced by a storm event in the previous 10 days was removed. The results for Four Corners and Montezuma Creek appear in Figures 3.41 and 3.42, showing the relationships for pre-peak and post-peak conditions. Even with this filtering, no statistically significant relationship exists, although there is an apparent difference between ascending and descending limbs of the hydrograph. To demonstrate the storm influence on sediment concentration, the Four Corners data were plotted together with the

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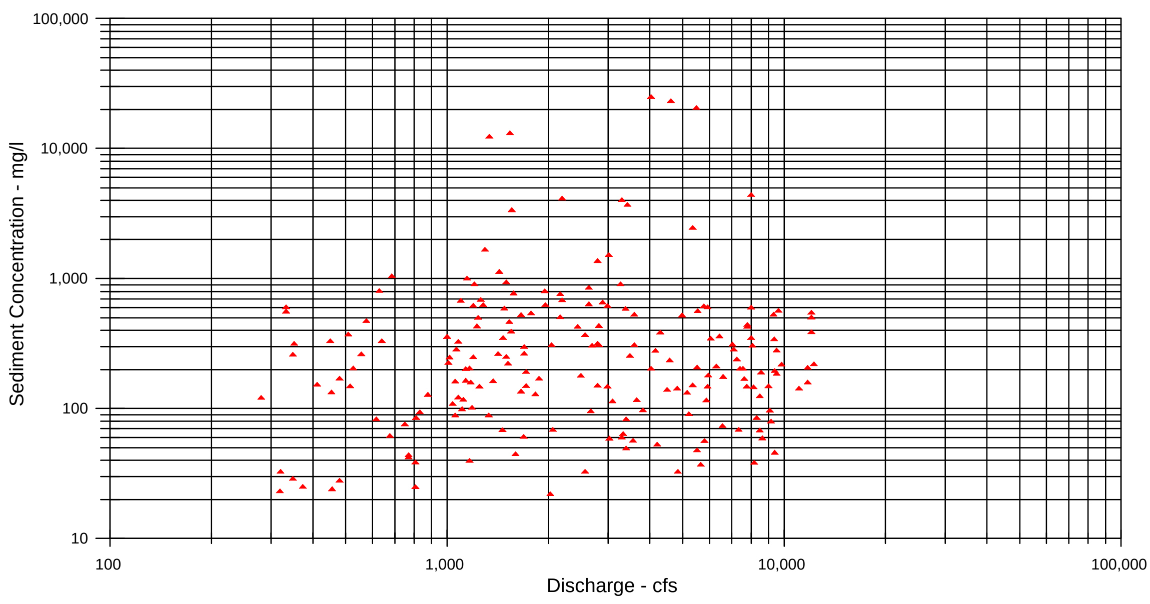

Figure 3.36. Suspended sediment vs flow for the San Juan River at Farmington, 1992-1998.

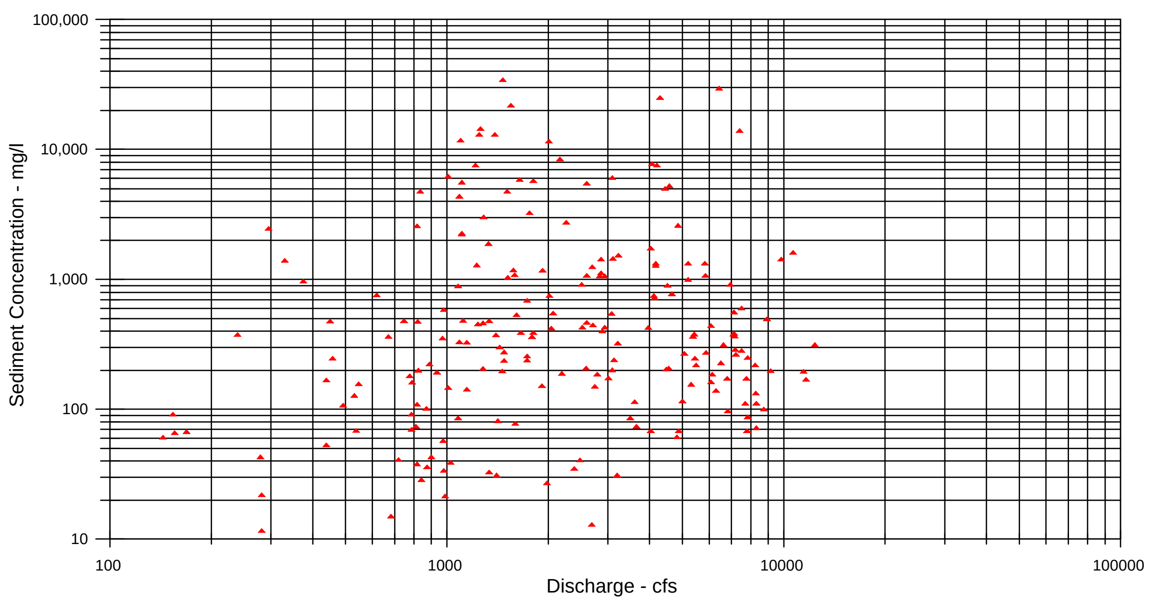

Figure 3.37. Suspended sediment vs flow for the San Juan River at Shiprock, 1992-1998.

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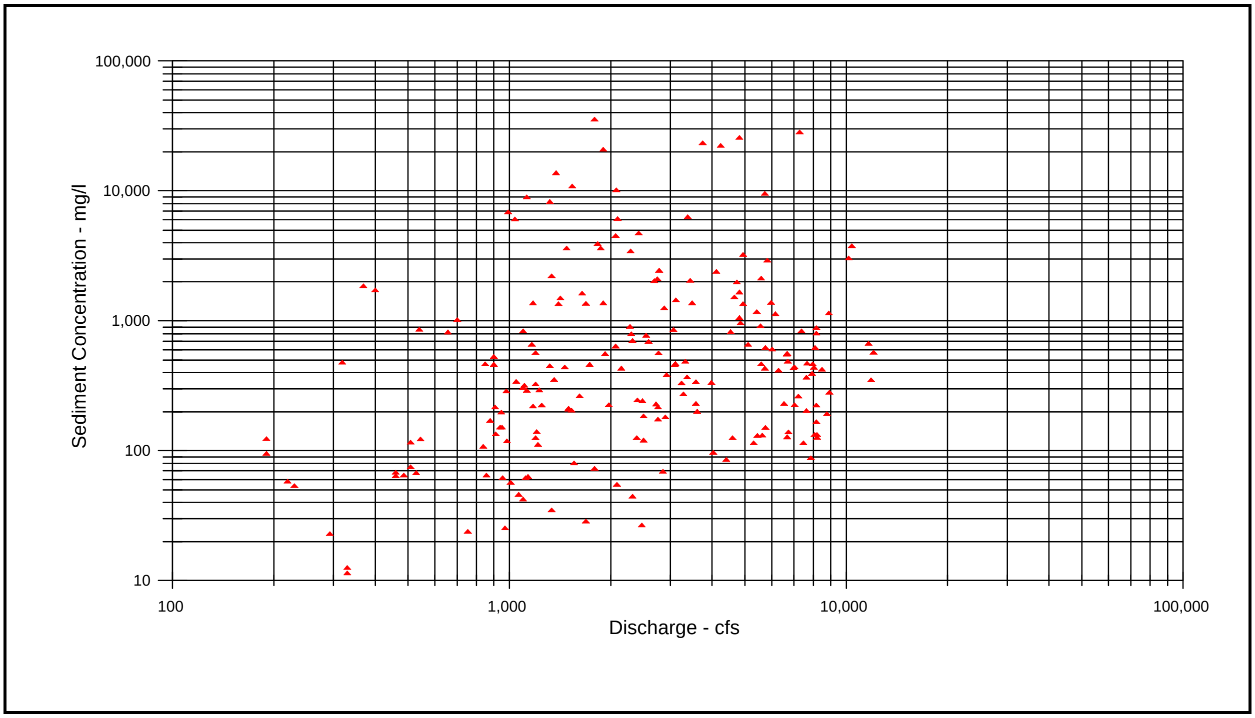

Figure 3.38. Suspended sediment vs flow for the San Juan River at Four Corners, 1992-1998.

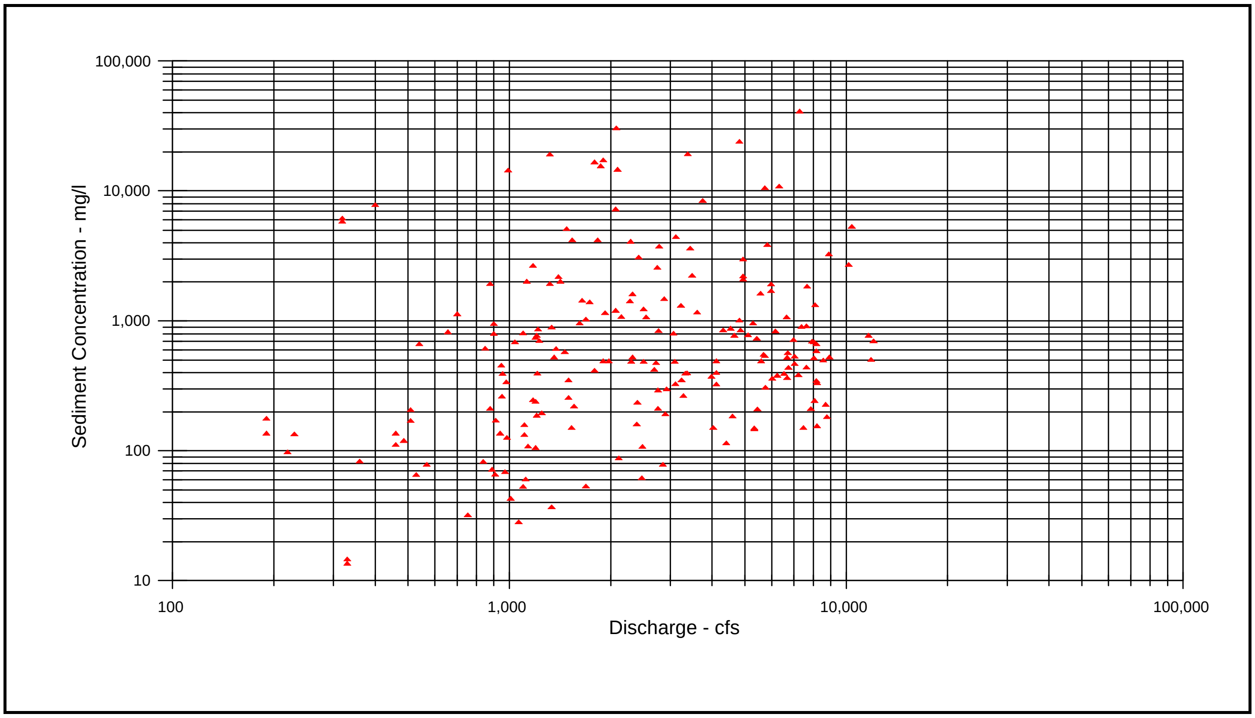

Figure 3.39. Suspended sediment vs flow for the San Juan River at Montezuma Creek, 1992-1998.

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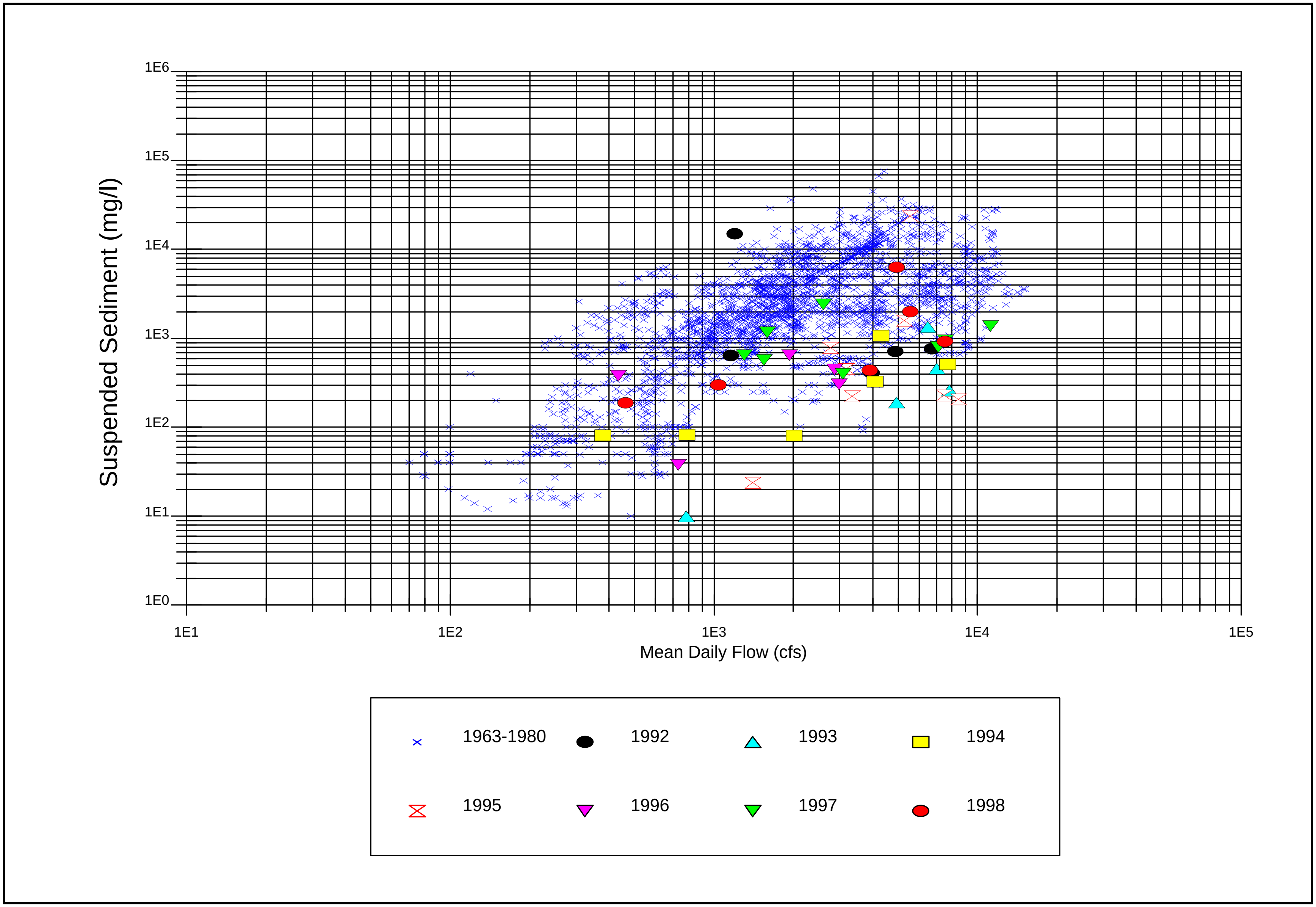

Figure 3.40. Suspended sediment vs flow for the San Juan River at Bluff, 1960-1983 compared to 1992-1998.

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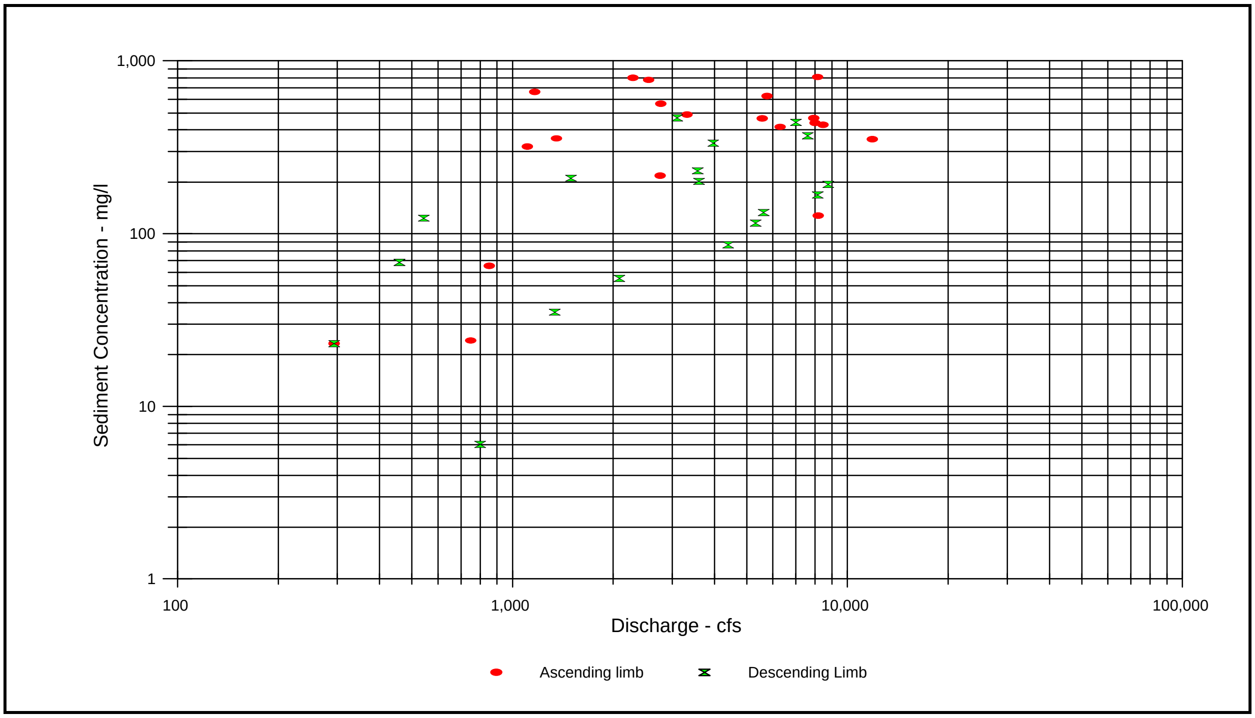

Figure 3.41. **Suspended sediment vs flow for the San Juan River at Four Corners, 1992-1998, for non-storm influenced samples.**

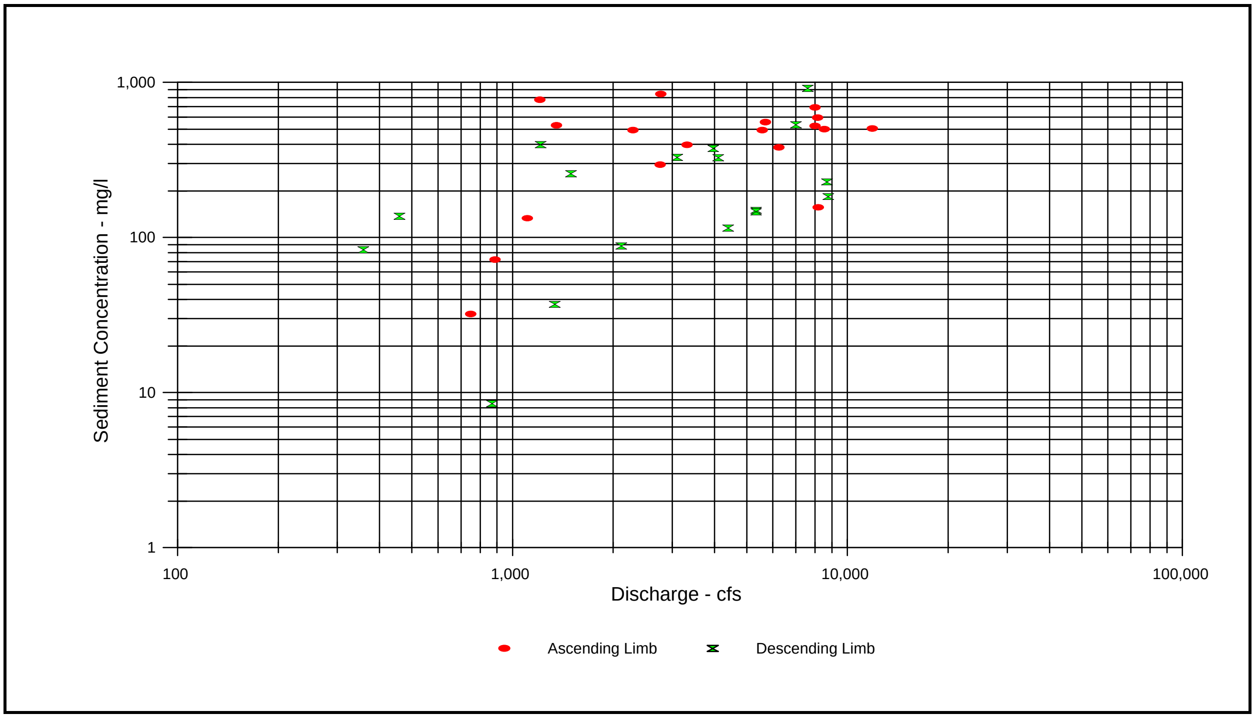

Figure 3.42. **Suspended sediment vs flow for the San Juan River at Montezuma Creek 1992-1998, for non-storm influenced samples.**

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hydrograph in Figure 3.43. The storm event influence can be seen by the extreme elevation in sediment concentration during increases in flow. In some cases, a very small increase in flow resulted in a large increase in sediment concentration due to the high concentration of tributary inflow. During one sampling trip, the sediment concentration in Chinle Wash was over 13% with a flow of 170 cfs. That one tributary increased the sediment concentration in the San Juan River below that point by 3700 ppm.

Due to the myriad of inflow points and the impracticality of measuring all the inflow concentrations on a sufficiently high frequency to allow computing mass balance, it was not possible to compare sediment transport to change in cross-section. The data collected have been used in fine sediment transport analysis for prediction of backwater flushing requirements.

DISCUSSION

Historic Analysis of Fluvial Morphology

Typically, we think of a desire to restore a river to its "natural" function through such activities as habitat restoration and mimicry of a natural hydrograph. In the case of the San Juan River, determining what this "natural" function was is difficult. No quantitative data and little qualitative data are available prior to the early part of the 20th century, yet the impact of man in the basin was strongly felt by then. The condition of the river in the 1930's when our earliest quantitative data are available is likely not the condition to which we would desire restoration. The lower portion of the river, including the canyon, was heavily sediment laden. There was no stability to the channel and most of the cobble was probably buried in 0.3 to 2.0 meters of sand.

By the early 1950's when the next aerial photography was available, not only had there been a significant shift in suspended sediment load in the system, allowing the channel to scour the sand from the system and form a more defined channel, but invasion of tamarask had begun, with substantial establishment by this period. The smaller, stabler channel was quite different than the 1930's channel. The larger, stabler islands likely led to more stability in the complex habitats typically associated with islands and the secondary channel system became more developed, especially in the lower three reaches. This was likely a positive development, although the depletion of water in the summer for irrigation led to extremely low flows in these reaches which was likely detrimental.

By the time Navajo dam was constructed in the early 1960's, the channel had stabilized even more, although the mean bankfull channel width was about the same as a decade earlier. With stabilization came a loss of channel complexity with fewer and smaller islands. The loss of bankfull islands is somewhat perplexing. It is possible that vegetation encroached into the shallower secondary channels during this drier than normal period. At high flows there would have been flooding, but possibly inadequate stream power to remove the tamarask, resulting in a simpler bankfull channel. On the aerial photos, the vegetated secondaries would not have been included in the bankfull channel area.

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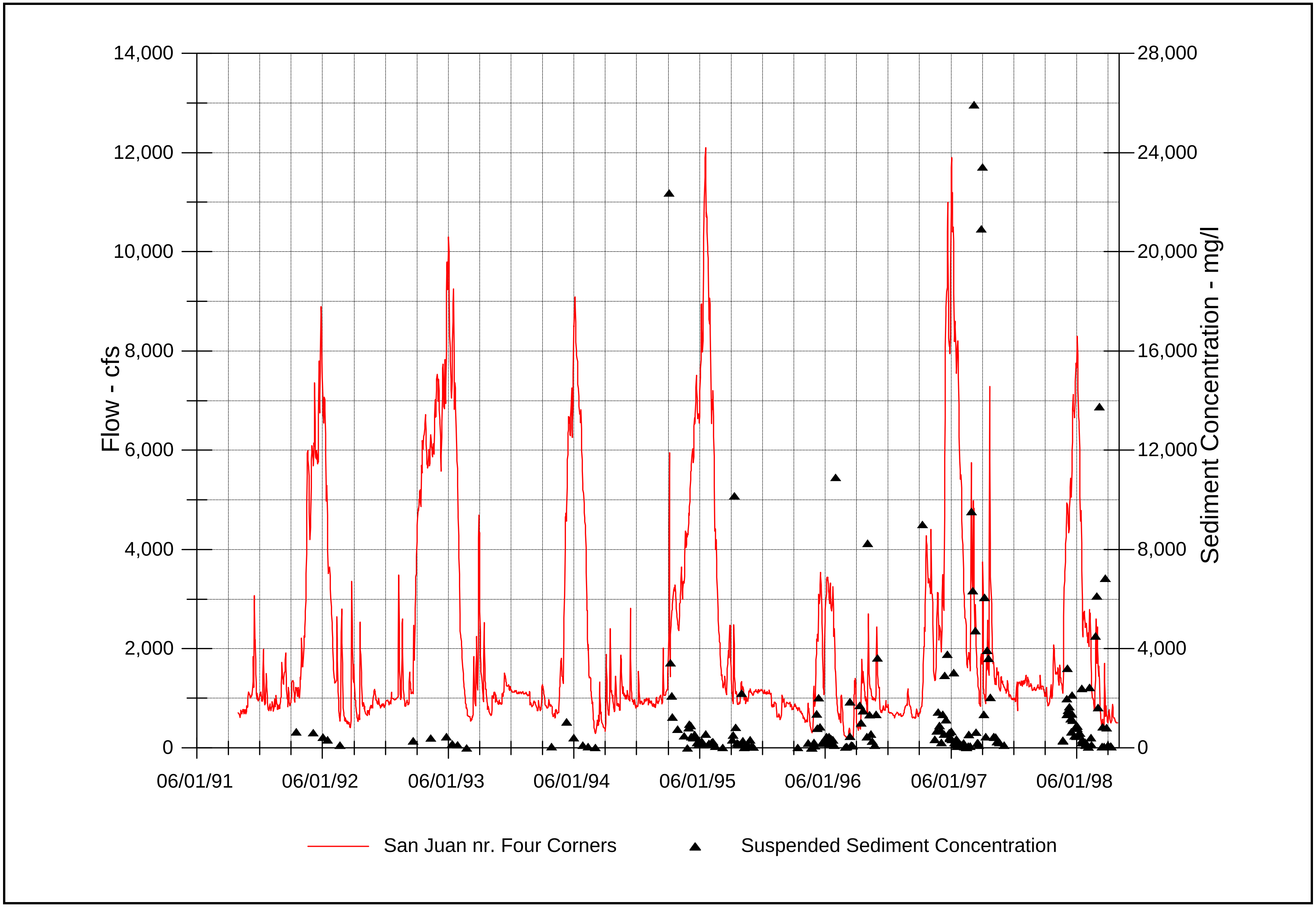

Figure 3.43. Daily flow and spot suspended sediment concentration for the San Juan River at Four Corners, 1994-1998.

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Between the early 1960's and 1988, the channel became much smaller, but in the process, gained significant island area and island count. Since the bankfull channel area lost is almost equal to the island area gained, it appears that previous sand and cobble bars became vegetated during this period of reduced spring peak flows. The channel is much more stable and is now heavily armored with Russian Olive along most of its course. The loss of bankfull channel capacity, estimated at between 15% and 30%, now requires less flow for channel maintenance and out-of-bank conditions occur at reduced flows.

The effect of introducing higher spring flows into this channel has resulted in a small increase in channel capacity, with channel complexity remaining relatively constant. The higher flows dislodge Russian olive trees along the banks, adding debris piles and habitat complexity.

Since no habitat mapping was completed prior to this research period, the actual change in aquatic habitat is not known. Nor is it known which of the channel conditions would be best for the endangered and other native fish.

Geomorphological Characterization

The eight geomorphological reaches identified allow analysis of system response to changed in hydrology to be analyzed on a finer resolution than considering the entire river. Further, sub-reaches are identified that can be utilized across all research studies to the extent that the boundaries are useful. The sub-reach definitions are based on characteristics that are distinct in terms of geomorphology and habitat, rather than arbitrary, or non-quantitative. To better relate the data presented in the analysis above to the conditions in the field, the following narrative descriptions are provided:

Reach 1: (RM 0 to 16, Lake Powell confluence to near Slickhorn Canyon) has been heavily influenced by the backwater effect and fluctuating reservoir levels of Lake Powell. Fine sediment has been deposited to a depth of about 40 ft in the lowest end of the reach since the reservoir first filled in 1980. This deposition of suspended sediment into the delta-like environment of the river/reservoir transition has created the lowest-gradient reach in the river. This reach is canyon bound with an active sand bottom. The thalweg meanders in the sand bottom, alternately creating scour (deep runs to sand shoals) and deposition (sandbars) along the thalweg at all discharges. At low flow (below 1,000 cubic feet per second (cfs)), backwaters form in mainchannel sandbars. At flows above 1,000 cfs, backwaters form in tributary mouths and invaginations in the canyon walls, and mainchannel backwaters are lost as the low sandbars are inundated. While this reach has the highest abundance (surface area per RM) of backwaters among the reaches studied, the backwaters are highly unpredictable and ephemeral due to the shifting thalweg, changing river flow, and fluctuating reservoir elevations that vary seasonally and annually.

Reach 2: (RM 17 to 67, near Slickhorn Canyon to confluence with Chinle Creek) is also canyon bound but is located above the influence of Lake Powell. The gradient in this reach is higher than in either adjacent reach and the fourth highest in the system. The channel is primarily bedrock confined and is influenced by debris fans at ephemeral tributary mouths. Riffle-type habitat dominates, and the major rapids in the San Juan River occur in this reach. Due to the steeper gradient, narrow canyon bottom, and low sinuosity, backwater habitats are small and scarce in this reach. Low-velocity habitats are primarily created as sand deposits in eddies below debris fans. While sandbar-associated backwaters are found, they are often associated with either debris fan/eddy complexes or eddy deposits below shoreline colluvium. Some oil development exists within an isolated area of floodplain in this reach, near the town of Mexican Hat, Utah.

Reach 3: (RM 68 to 105, Chinle Creek to Aneth, Utah) is characterized by higher sinuosity, lower gradient (second lowest), broad floodplain, multi-threaded channel, high island count, and high percentage of sand substrate. This reach has the second highest density of backwater habitats after spring peak flows, but is extremely vulnerable to change during summer and fall storm events, after which this reach may have the second lowest density of backwaters. As a result, this reach has been deemed the most highly responsive reach to extreme discharge events. While cobble is present in this reach, it is frequently mixed with sand. Areas of clean cobble are usually small and ephemeral. The active channel results in a large number of organic debris piles at lower flow created by dislodged Russian olive trees.

Reach 4: (RM 107 to 130, Aneth, Utah, to below the "Mixer") is a transitional reach between the upper cobble-dominated reaches and the lower sand-dominated reaches. It has the most bedrock contact of any reach. Sinuosity is moderate compared to other reaches, as is gradient. Island area is higher than in Reach 3 but lower than in Reach 5, and the valley is narrower than in either adjacent reach. Total water surface area is somewhat less at all flows than in the adjacent reaches. River banks are more stable in this reach than in Reach 3, and about the same as in Reaches 5 and 6. Backwaters in this reach are subject to perturbation from summer and fall storm events, but Reach 4 is not considered as responsive as Reach 3. Backwater habitat abundance is low overall in this reach (third lowest among reaches) and there is little clean cobble. Perturbation of secondary channels due to summer and fall storm discharges is a problem in this reach. One perennial tributary, the Mancos River, enters the San Juan River in this reach.

Reach 5: (RM 131 to 154, the "Mixer" to just below Hogback Diversion) is predominantly multi-threaded with the largest total wetted area (TWA) and largest secondary channel area of any of the reaches. Secondary channels tend to be longer and more stable than in Reach 3 but fewer in number overall. Riparian vegetation is more dense in this reach than in lower reaches but less dense than upper reaches. Cobble and gravel are more common in channel banks than sand, and clean cobble areas are more abundant than in lower reaches. Channel gradient in Reach 5 is steeper than in all lower reaches but flatter than Reaches 6 and 7. This is the lowermost reach where adjacent irrigated lands and irrigation return flow influence riparian vegetation and bank stability, and contribute to groundwater accretion. The river valley is broadest in this reach. One perennial tributary, Chaco Wash, enters the San Juan River in this reach. This is the lowermost reach containing a diversion dam (Cudei). This reach is much less subject to perturbation of backwaters and spawning bars during summer and fall storm events than the lower reaches, especially in the upper portion of the reach.

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Reach 6: (RM 155 to 180, below Hogback Diversion to confluence with the Animas River) is predominately a single channel, with 50 percent fewer secondary channels than Reaches 3, 4, or 5. Cobble and gravel substrates dominate, and cobble bars with clean interstitial space are more abundant in this reach than in any other. Irrigated land adjoins the river for the full length of this reach, often on both sides of the river. There are four diversion dams that may impede fish passage in this reach (Figure 2.1). Backwater habitat is low in abundance in this reach, with only Reach 2 having less. Gradient is the second steepest of all reaches, although about 10 percent of the elevation change occurs at the diversion dams, making the effective slope about the same as that in Reach 5. Two tributaries enter in this reach: the LaPlata River which carries little water to the San Juan River except during runoff, and the Animas River which is the largest tributary to the San Juan River in the study area. A third tributary, the Ojo Amarillo, is naturally ephemeral but is effectively perennial at present due to irrigation return flow. Irrigation return flow influences riparian vegetation and groundwater accretion in this reach. The channel has been altered by dike construction in several areas to control lateral channel movement and overbank flow.

Reach 7: (RM 181 to 213, Animas River confluence to between Blanco and Archuleta, New Mexico) is similar to Reach 6 in terms of channel morphology, with about the same secondary channel count, TWA, and valley width. Irrigated land adjoins most of this reach on both sides of the river, and groundwater accretion contributes to an increase in grass understory. The river channel is very stable in this reach. The reduction in magnitude of peak flows with the construction of Navajo Dam caused a reduction in overall shear stress and a reduced ability to move large-grained embedded cobble. In addition, much of the river bank has been stabilized and/or diked to control lateral movement of the channel and overbank flow. While the dominant substrate type is cobble, armoring has occurred that, coupled with the bank armoring and grass understory, limits availability of new cobble sources within this reach. Water temperature in this reach is influenced by the hypolimnetic release from Navajo Dam and is colder during the summer and warmer in the winter than the natural river. Sediment load is also reduced due to the sediment-trapping influence of the dam and limited tributary influence resulting in relatively clear water compared to downstream reaches.

Reach 8: (RM 213 to 224) is the most directly influenced by Navajo Dam, which is situated at its uppermost end (RM 224). This reach is predominantly a single channel, with only four to eight secondary channels, depending on the flow. This reach has the lowest number and TWA of secondary channels of any reach above the lower canyon (Reaches 1 and 2). The valley narrows in this reach, with less irrigation influence and less artificial stabilization of the channel. Cobble is the dominant substrate type, and because lateral channel movement is less confined in this reach, some loose, clean cobble sources are available from channel banks. In the upper end of the reach just below the dam, the channel has been heavily modified by excavation of material used in dam construction, thus also modifying gradient and channel morphology. In addition, the upper 6.2 mi of this reach above Gubernador Canyon are essentially sediment free, resulting in the clearest water of any reach. Because of Navajo Dam, this area experiences much colder summer and warmer winter temperatures. These cool, clear water conditions have allowed development of an intensively managed blue-ribbon trout fishery to the exclusion of the native species in the uppermost portion of the reach.

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River Geometry Analysis

The response of the river to the test flows is best seen in the response in the cross-sections established for this study. The model developed for scour as a function of the previous year's deposition and the total volume of flow during the runoff period is significant and describes 95% of the variability in scour at the RT transects, considering the average change for all cross-sections. The data and the model both indicate that the river is approaching a new dynamic equilibrium, with a 7 - 10% increase in channel cross-sectional area. While not all cross-sections respond the same, the deviations from this model are explained by the conditions at the individual transects.

The mixer and debris field transects are more variable, as would be expected from their locations. However, these transects also show a general trend of scour with time.

To put this change in perspective in the long term, channel response at USGS gage locations were examined. At both the Farmington and Shiprock gages, the historic changes have been greater than anything measured at the transects. During the test flow period, the Shiprock gage shows a trend similar to the study transects, with an initial scour and then relative stability. The Farmington gage did not show any change in trend due to the restored flows. This gage has been in a general trend of deposition since 1942 and that trend is continuing, with a large gravel bar building down from the bridge that is just upstream of the gage. In the case of both gages, the variation in average bed elevation from year to year is less after the dam. However, the dam does not appear to have influenced the general trend at either gage.

Along with the change in bed elevation has come an increase in the percent of cobble substrate with the higher flows. This is especially true following runoff. Much of the exposed cobble is again covered with sand during the non-runoff period, only to be exposed again during runoff. The increase in cobble substrate could lead to increased primary productivity in the system with time.

The relatively strong (r^2 = 82%) correlation between scour and days with flow above 5,000 cfs indicates the ability of these flows to move sediment from the main channel. Other correlations are not strong or are not significant.

The analysis of cobble movement vs flowrate, indicates that some cobble moves, especially in the higher gradient areas over bars, at 2,500 cfs or less. Since no measurements were taken in periods when the flow did not exceed 2,500 cfs, it has been assumed that 2,500 cfs is the threshold for moving cobble to provide open interstitial space on existing bars. It is likely that some cobble moves at flows lower than 2,500 cfs on many bars, but the data are not available to verify that hypothesis. While the 2,500 cfs may be considered a conservative (high) estimate of the required flow, the amount of cobble movement below 2,500 cfs would likely diminish the available clean cobble for spawning. Since this is not a particularly difficult flow to achieve, sufficient cobble movement to provide suitable spawning occurs nearly every year.

The trend of cumulative scour at the cross-sections suggests the potential for channel simplification as secondary channels are isolated at lower flows. Analysis of the trend in island count at low flow through 1994 suggested that some simplification was occurring. In 1995, this trend reversed, with an increase in islands in response to out-of-bank flows. Since the island count has seen no net change over the test period, channel simplification is not likely to occur with mimicry of the natural hydrograph, as long as periodic out-of-bank flows occur. Since this conclusion is based on a short period of record, continued monitoring is recommended to verify that the channel is not being simplified.

The scour that has occurred has resulted in an increase in bankfull channel capacity of about 12% over the research period to an average flow of about 8,000 cfs. Since the bankfull channel area is still much less than during pre-dam conditions, the historic bankfull capacity was likely greater than 8,000 cfs, although now measurements have been made to quantify the historic bankfull discharge.

Cobble Bar Characterization

Characterization of cobble bars in the San Juan River indicates that there are multiple locations that have characteristics similar to the Yampa spawning bar in terms of cobble size distribution, suggesting that they are suitable for spawning as well. Cobble bar sampling from RM 76 to RM 173 indicated that the size of cobble does not change with distance down river in the bars sampled. Since the channel gradient and discharge do not change appreciably in the area studied, the consistency of cobble size is not surprising.

Also not surprising is the finding that the bars increase in the depth of open interstitial space with distance up-river. The finding coincides with the geomorphological characterization and habitat mapping that indicate an increase in abundance of sand substrate with distance downstream..

While the area of bars that contain appreciable depth of open interstitial space changes from year-to-year in response to cleaning and subsequent filling by sediment laden storm events, in all years surveyed, areas of open interstitial space in excess of two mean cobble diameters existed. The area diminished in years of low runoff or in situations of storm events occurring before the survey was completed, but was always present.

Based on an assumption that open interstitial depth of 2 mean cobble diameters is adequate for spawning, it appears that in all survey years suitable gravels in locations that exhibit the physical characteristics associated with spawning in 1994 were available for locations above RM 131. Conditions below RM 131 are less suitable, but not proven to be inadequate.

Flows to Support Cobble Transport

Based on the results of the studies conducted to date, it is concluded that sufficient local cobble movement exists to provide some clean cobble for spawning with flows of 2,500 cfs or higher for a duration of at least 10 days prior to spawning. The threshold flow of 2,500 cfs is determined from

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data in Table 3.22 indicating cobble movement at flows at or below 2,500 cfs. The 10-day duration is based on qualitative assessment of the data in Table 3.22, coupled with field observation of bar reshaping. Duration of flows at about 2,500 cfs for as little as 1 day indicate cobble movement, but there were extended periods at marginally lower flows, as these conditions typically occurred between the summer and following spring measurements. The March to July 1996 period demonstrated substantial cobble movement with 36 days above 2,500 cfs, and March to May 1994 indicated large cobble movement in the Mixer with 14 days above 2,500 cfs, although flows exceeded 5,000 cfs for this period. While no data precisely indicate the minimum required duration, the 10-day duration was selected as the minimum threshold because it falls within the results summarized above and is considered reasonable based on field observation. Longer durations at somewhat lower flows may serve the same function as indicated by the pre-runoff conditions in 1996, but there is insufficient information to conclude threshold conditions lower than 2,500 cfs.

The bankfull flow of 8,000 cfs was selected as the flow required for cobble transport and bar building based on model results of the four research reaches reported in Table 3.31, and flow calculations at the RT cross-sections; it is qualitatively supported by the decrease in island area and count at flows somewhere between 6,500 and 7,700 cfs (Figure 3.29). Examination of the cobble movement data reported in Table 3.22 suggests an 8-day duration as appropriate for the minimum duration necessary for bar-building cobble transport. This minimum duration is based on the channel cross-section data indicating measurable cobble movement with as few as 3 days at 8,000 cfs and substantial cobble movement after 13 days. The two durations were averaged to arrive at the recommended value. The flow/duration criteria were analyzed for adequacy of channel maintenance by examining historical conditions since the closure of Navajo Dam. During this time period, cross-section surveys indicated a narrowing and deepening of the channel, especially in the higher reaches (5 and 6), with a recurrence frequency of about 1 year in 4 years for flows of 8,000 cfs for 8 days. Since some channel capacity was lost under these conditions, an increase in the average frequency of bankfull flows is needed to prevent further lost capacity and possibly assist in restoring some of the capacity already lost. An average recurrence frequency of 1 year in 3 years (33%) will increase the frequency of conditions necessary for maintenance of channel capacity. Therefore, 8,000 cfs for 8 days with an average recurrence frequency of 1 year in 3 years are the conditions recommended for cobble bar construction and channel maintenance. From a sediment-transport and channel-maintenance standpoint, the full range of flows from 2,500 cfs through 10,000 cfs plays an important role. Mimicking a natural hydrograph that includes flows in this range is necessary. Just providing the conditions required at 8,000 cfs would be inadequate and could lead to channel simplification and armoring over time. Because of the short period of study, monitoring should continue to verify these relationships.

Flows above 10,000 cfs are recommended periodically for maintaining channel complexity and floodplain integrity. The response of islands to flows shown in Figure 3.29 indicates that flows less than 10,000 cfs (1992 to 1994) may result in channel simplification with time unless combined with higher flows that develop new secondary channels and islands through overbank flow (1995). Examination of the flow record indicates a duration of 6 days at Bluff and 11 days at Four Corners, with a resulting increase in islands above pre-research period levels providing conditions that were more than adequate for maintenance of channel complexity. High flows are the most-altered portion

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of the natural hydrograph in the San Juan River. Historically, these flows have played a major role in floodplain development. While all the mechanisms of importance have not been identified and quantified during the research period, the general paradigm of natural flow mimicry would not be met without restoration of these higher flows to some degree. Therefore, a conservative threshold requirement of 5 days at or above 10,000 cfs was selected for purposes of natural flow mimicry and maintenance of channel complexity.

The cobble bar maintenance flow (2,500 cfs) should occur at a frequency sufficient to ensure long-term reproductive success of the species of interest. The cobble bar construction flow (8,000 cfs) is needed less frequently if bars are maintained (cleaned and reworked) on a regular interval. Data suggest that the bars can be reworked to provide clean cobble for several years without the necessity of reconstruction or replacement. Channel maintenance requirements indicate an average recurrence of 1 year in 3 years for flows above 8,000 cfs. The 10,000-cfs flow condition is not required as frequently. Historically, it had been 8 years between the occurrence of these conditions (1987 and 1995). Looking at the potential for channel complexity deterioration indicated in Figure 3.29, the required average recurrence frequency for maintenance of channel complexity and floodplain integrity was determined to be 5 years. During the pre-dam period, the 10,000-cfs flow conditions were met 39% of the time (4 years in 10, vs. 2 years in 10 in this recommendation). The reduction in channel capacity that has occurred since the closure of Navajo Dam allows a lower frequency of achieving these conditions. Given the short duration of the studies upon which these recommendations are based, future refinement of the recommendations will likely be necessary, thus requiring an adaptive management approach.

Low Velocity Habitat Maintenance - Measurement of Change in Sand/Cobble Bars

During the course of the research period, no relationship was developed between spring runoff conditions and bedform structural change influencing backwater formation. Studies of bar change did not indicate a relationship between bar height and peak runoff magnitude or volume for the range of flows tested, likely because most peak flows were at or above bankfull where stage and shear stress change little with change in flow. Further, a large percentage of backwaters are associated with secondary channel or tributary mouths. Therefore, the structural studies concentrated on backwater cleaning processes.

Detailed monitoring and modeling of fine sediment transport in two secondary channel associated backwaters indicated flows must be in the 4,000 - 5,000 cfs range to initiate cleaning. Further, flushing is improved by longer durations and higher magnitudes of spring flows. Both backwaters begin to refill with sediment on the descending limb of the hydrograph. Modeling indicated that steeper descending limbs tended to limit the amount of deposition. Summer storm events can fill in these backwaters during heavily perturbating (multiple sediment laden storm events in one season) years. Modeling is very sensitive to sediment concentration and grain size distribution, making it difficult to accurately predict performance in a non-calibration year. So far, each year analyzed has required a separate calibration, with low accuracy of predicted results. For accurate modeling, at

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least daily sediment concentration and size distribution would be required. It also may be that sediment transport through the secondary channel forming the backwater has less course material that would result from the bedload in the main channel due to the elevated nature of the inlets of most of these secondary channels. Calibration shows that finer sediment size than measured in the main channel is required to achieve a match with measured channel conditions. For modeling to be effective, more intense sediment concentration data would be needed and possibly a more robust model. The conclusions here are based most strongly on the monitoring data and response to flows rather than the modeling results.

Suspended Sediment Analysis

In any study of fluvial morphology it is desirable to be able to measure sediment inflow and outflow to determine the sediment balance. While this is possible for non-storm influenced periods in the San Juan, it is not practical to measure all the inflows required in the San Juan River due to the numerous inflows. The sediment data collected did indicate that the concentrations measured fall within the range of historic sampling, although averages were on the low side of the historic mean This could represent a shift to lower sediment concentrations, or indicate a sampling bias as the non-runoff period was not sampled.

Sufficient analyses have been completed to now that the system is heavily perturbated by summer and fall storm runoff events, where measured tributary inflow concentrations of total suspended solids (tss) have been as great as 130,000 ppm (13%). These heavy sediment contributions lead to reduced backwater habitat quality and require more frequent flushing to maintain system health.

CONCLUSIONS

History of Fluvial Morphology

- There has been substantial change in the geomorphology of the San Juan River since the early 1930's.
- Much of this change is associated with change in suspended sediment load and in the riparian vegetation community and density.
- A portion of the change, especially in the reduction of channel capacity, has occurred as a result of the modified hydrology as a result of the operation of Navajo Dam
- Data do not exist to determine if the habitat conditions for the fish are better or worse today than at other times in history for the habitat range that is presently available. Given the change in available range, it is clear that there has been a significant overall reduction in available habitat.

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Change in Channel Morphology with Test Flows

- Test flows since 1991 have further modified the geomorphology net scour in the system resulting in an increase in channel capacity of about 12%.
- This scour seems to be stabilizing to a new dynamic equilibrium condition, although it is too soon to assure that this is the case.
- The amount of scour is less than the normal range of scour and subsequent deposition that has been observed at USGS gages over the past 50+ years, indicating that there will not be catastrophic change in the channel as a result of continued mimicry of a natural hydrograph.
- Flows at 2,500 cfs or greater transport sufficient cobble on the higher gradient portions of bars to develop clean locations for spawning. A duration of 10 days is adequate, with frequencies sufficient to support regular spawning required.
- Flows greater than 5,000 cfs are associated with scour at the cross-sections measured, with the amount of scour being moderately correlated to days above 5,000 cfs. It is assessed that flows of 5,000 cfs or more for 21 days are adequate to clean backwaters and these conditions should exist at least every other year, on average.
- Bankfull channel capacity is estimated to average about 8,000 cfs between Farmington and Bluff, representing an increase of about 12% during the research period

Cobble Bar Characterization

- Cobble bars exist in the system that appear to have conditions suitable for spawning. The conditions are better above RM 131 than below and are comparable to conditions on the Yampa spawning bar.
- There appears to be ability to transport cobble through low gradient reaches of the system to maintain a sediment balance, although this transport likely occurs at a low rate on average, with local, periodic high rates of transport for short distances.

Low Velocity Habitat Creation and Maintenance

- Surveys of two main channel sand/gravel bars associated with backwaters indicate that the bars were erosional in nature and that high flows created scour along the margin and eventual loss of the backwaters.
- Increased flows did not increase the height of the bars, which did not change appreciably over the course of the study period. This finding is counter to findings in the Green River. Since most peak flows were at or above bankfull, the actual stage did not change markedly from year to year, explaining the reason for the limit on bar height.
- Bar height in Reach 1 did increase, but in response to Lake Powell elevation rather than stage during runoff. Geomorphology of the river in Reach 1 appears to as influenced by lake level as discharge.
- Maintenance of backwaters occurring at the mouths of isolated secondary channels is related to flows above 5,000 cfs, the approximate threshold flow for initiation of flushing of these backwaters.

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- These backwaters tend to scour through runoff and refill on the descending limb and during subsequent sediment laden storm events. Steeper descending limbs and longer peak runoff favor cleaner backwaters.

Suspended Sediment Analysis

- Suspended sediment concentration appears to be similar to historic conditions and is typically higher during summer storm events than during spring runoff. Summer storms of small magnitude can generate high sediment concentrations when they originate in small, unprotected watersheds in the lower portion of the basin.
- It was not possible to compute a sediment balance for the study area due to the many small tributaries that contribute large volumes of sediment during short duration storm events.